Incremental Model-to-Text Transformation

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Abstract

Model-driven engineering (MDE) promotes the use of abstractions to simplify the development of complex software systems. Through several model management tasks (e.g., model verification, re-factoring, model transformation), many software development tasks can be automated. For example, model-to-text transformations (M2T) are used to realize textual development artefacts (e.g., documentation, configuration scripts, code, etc.) from underlying source models.

Despite the importance of M2T transformation, contemporary M2T languages lack support for developing transformations that scale. As MDE is applied to systems of increasing size and complexity, a lack of scalable M2T transformations and other model management tasks hinders industrial adoption. This is largely due to the fact that model management tools do not support efficient propagation of changes from models to other development artefacts. As such, the re-synchronisation of generated textual artefacts with underlying system models can take considerably large amount of time to execute due to redundant re-computations.

This thesis investigates scalability in the context of M2T transformation, and proposes two novel techniques that enable efficient incremental change propagation from models to generated textual artefacts. In contrast to existing incremental M2T transformation technique, which relies on model differencing, our techniques employ fundamentally different approaches to incremental change propagation: they use a form of runtime analysis that identifies the impact of source model changes on generated textual artefacts. The structures produced by this runtime analysis, are used to perform efficient incremental transformations (scalable transformations). This claim is supported by the results of empirical evaluation which shows that the techniques proposed in this thesis can be used to attain an average reduction of 60% in transformation execution time compared to non-incremental (batch) transformation.

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In memory of my mum, Mrs. Olufunke Anthonia Ogunyomi

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Declaration of Authorship

I declare that the contents of this thesis are the outcome of my own research that was conducted between October 2012 and November 2015. This work has not previously been presented for an award at this, or any other University. All sources are acknowledged as References. Parts of this thesis have been previously published in the following:

- **On the use of Signatures for Source-Incremental Model-to-Text Transformation.** Babajide Ogunyomi, Louis M. Rose, Dimitris S. Kolovos. *Proceedings of the 17th International Conference on Model-Driven Engineering Languages and Systems (MoDELS 2014)*, Valencia, Spain, September 28 - October 3, 2014.
- **User-defined Signatures for Source Incremental Model-to-text Transformation.** Babajide Ogunyomi, Louis M. Rose, Dimitris S. Kolovos. *Proceedings of the Workshop on Models and Evolution co-located with ACM/IEEE 17th International Conference on Model Driven Engineering Languages and Systems (MoDELS 2014)*, Valencia, Spain, Sept 28, 2014.
- **Property Access Traces for Source Incremental Model-to-Text Transformation.** Babajide Ogunyomi, Louis M. Rose, Dimitris S. Kolovos. *Proceedings of the 11th European Conference on Modelling Foundations and Applications (ECMFA 2015), Held as Part of STAF 2015*, L'Aquila, Italy, July 2015.

Chapter 1

Introduction

Software is ubiquitous. Its use cuts across many industries and different platforms. Software is relied on by health practitioners, aircraft manufacturers, defence, social media etc. With such reliance on software also comes demand for increasingly more sophisticated software which is essentially a confederation of systems with intricate interconnections, e.g., enterprise systems. Diversification of operating environments and heterogeneity of development tools have led to an increase in the complexity of software systems. However, the complexity of such software systems has made it difficult for developers and other stakeholders to specify, design and implement them. In response to the challenge of developing complex systems, the entire history of software engineering has been of the rise in levels of abstraction [4]. For example, the main motivation for the development of high-level programming languages was to bridge the gap between human understanding and computer. As software increased in complexity, it became more difficult to develop and maintain them in low-level programming languages [5]. Before the introduction of compilers, developers had to write software in a format directly interpretable by computers. Since then, assembly programming languages (e.g., PL360 [5]) have given way to high-level programming languages such as object-oriented languages [6] (e.g., C++, Java). Raising levels of abstraction continues to be used to tackle software complexity because it enables developers to focus on essential aspects of a problem while less attention is on implementation details. Model-driven engineering is founded on the same principle, raising levels of abstraction to improve software quality and productivity.

1.1 Model-Driven Engineering (MDE)

MDE is a software engineering discipline with the aim of bridging the gap between the conceptual complexity of software systems and their implementation. MDE aims to reduce system complexity by raising levels of abstraction and increasing the ability to automate software development tasks, e.g., analysis, coding, testing, etc. Appropriate abstractions of systems reduces complexity, eases understanding, and reduces the risk of errors in large systems [7]. In MDE system complexity is addressed through the use of models. Models are abstract representations expressed through high-level concepts of the system domain. Through model management techniques such as model transformation, validation, merging, weaving, etc., several software development tasks can be automated. This results in the improvement of software quality because design flaws can be detected early through model analysis, and it also reduces development time [8–10]. For example, systems can be realized through automatic code generation, translation of models to other types of representations, etc.

Model transformation is a commonly applied model management technique in MDE. Model transformation is the process of translating elements in source models to other forms of representations through defined translation specification. A transformation specification comprises transformation rules which define mappings between source and target models. There are two types of model transformations: model-to-model (M2M) and model-to-text (M2T). M2M transformations translate models to other types of model representations. On the other hand, M2T transformations produce textual artefacts. M2T transformation is an important model management task whose applications include model serialization, visualization, code and document generation [11].

1.2 Software Evolution in MDE

Software evolution describes the changes that are applied to a software system over time [12]. Its study includes understanding the factors that are commonly responsible for software changes, activities and techniques used to accommodate the changes, and the costs associated with the evolution. Changes are inevitable in the life cycle of software systems. About 75% of changes to software are due to changing development environments and emergence of new user requirements [13]. Accommodation of changes to software however incurs costs associated with the analysis of required change and its impact, implementation of the change, revalidation and testing, and the possible introduction of errors into the software product [14, 15]. As such, Sommerville describes software evolution as a necessary, but expensive process [16, Chapter 21].

In MDE, models assume prominent roles where they are treated as first class artefacts of a software development process [17]. Other artefacts of a system development process, e.g., code, documentation, other system representations, depend on the source models. Whenever the underlying models of a system evolve, other dependent artefacts have to evolve accordingly [18]. Specifically, models and other artefacts need to be continually kept in sync (typically through model transformations) in order to maintain consistency across all artefacts. However, despite the benefits of MDE, model management tasks such as model transformations scale poorly. As sizes of models increase, model management tools lack the capability to cope without degradation in performance [19]. Similarly, when models evolve transformation tools do not support efficient propagation of the changes which results in redundant re-computations. This has been the subject of much research work in the context of M2M transformation. However, lack of scalability remains an open research problem in M2T, and it is the focus of this research project.

1.3 Motivation

As MDE is applied to systems of increasing size and complexity, a lack of scalability in M2T (and other) transformation languages hinders industrial adoption. Contemporary M2T tools do not support source-incrementality, hence they are not amenable to efficient change propagation. Source-incrementality is a special type of incremental transformation in which only affected parts of a transformation are re-executed. In the absence of source-incrementality, a transformation engine responds to input model changes by re-executing the transformation in its entirety (i.e., on all parts of the input model). Consequently, the amount of time expended by a transformation engine during an initial execution of a transformation is the same as the amount of time expended re-executing the same transformation, even when only a small fraction of the input model is changed. As such, they are impractical in an environment where changes are frequent.

Ideally, the re-execution of a transformation should be limited to the affected parts of the input model in order to reduce redundant re-computations, and potentially transformation re-execution time. The amount of time and effort required to re-generate text files from models when changes occur to the models, should be proportional to the magnitude and impact of the change(s), rather than to the sizes of the input models. A transformation tool must be able to cope with the propagation of changes from large models to dependent artefacts with minimal redundant re-computations and without diminishing performance. However, efficient propagation of changes from models to

generated artefacts remains a prominent challenge in M2T transformation implementations.

1.3.1 Example

The initial motivating example for this research is the INESS EU funded project (EC FP7, grant #218575) which used M2T transformation to generate code from UML models (in the railway domain). Specifically, it entailed automatic generation of PROMELA ([20]) and mCRL2 ([21]) code from the UML input model. The input model was about 20 MB on disk. The generated code was the implementation of an automated analyser for UML models of railway junctions to determine inconsistencies between requirements and system properties that are defined by railway engineers [22].

A subset of the M2T transformation which was responsible for the generation of mCRL2 code required about 7 hours to execute. Observations during the INESS project revealed that the M2T transformation required the same amount of time to re-establish consistency between the source model and the generated code, even when small changes were applied to the underlying source model. This is because the implementation language of the transformation did not support source-incremental transformations. In addition to this, a single part of the transformation was responsible for generating considerable large proportion (99%) of the generated code. Such monolithic design hinders the applicability of incremental techniques to transformations because in such scenarios, change impact is often 100%, i.e., all dependent artefacts are affected by the changes.

1.4 Research Aims

The primary focus of this research is to investigate and identify bottlenecks in M2T transformation methods, design and implement suitable method(s) that would allow for increased efficiency of M2T transformations. Typical M2T languages and tools that the author has found in literature and in the development community (Eclipse and Visual Studio platforms), only support either target incrementality and/or user edit-preserving incrementality.

1.5 Hypothesis and Objectives

The primary focus of this research is to investigate and identify bottlenecks in M2T transformation methods, design and to develop suitable technique(s) that would allow for increased efficiency of M2T transformations. Typical M2T transformation engines operate as follows. They re-execute by running the transformation against all source model elements irrespective of the effect of the changes. This often leads to the re-generation of files whose contents are not altered by the source model changes. Such re-execution strategy at best only compares newly generated output with the contents of a previously generated file to determine whether to overwrite the previously generated file. It is important to note that at the point when the transformation engine decides whether to overwrite a file, redundant re-transformation has already occurred.

Ideally, an incremental transformation should be selective - only changed model elements and affected parts of the transformation should be re-executed. This will eliminate redundant re-transformations and re-generation of files which have not been impacted by the change(s) to the source model(s). This ideal is only achievable through source-incremental transformations that restrict re-execution to the changed parts of the source model. Hence, we define a scalable transformation as one in which the re-execution time following a change in its input model is proportional to the impact of the change rather than to the size of the input model. Transformations that fully exercise an entire input model regardless of the impact of the input model changes, do not scale with respect to transformation re-execution time.

Therefore, the hypothesis of this thesis is stated thus:

- *Contemporary approaches to M2T transformations can be extended with novel and practicable techniques which enable correct and efficient source-incremental transformations without sacrificing the expressiveness of the M2T language.*
- *There exists a threshold of the proportion of model changes at which source-incremental execution ceases to be more efficient than non-incremental execution of a M2T transformation.*

Based on this hypothesis, the objectives of this thesis are:

1. To investigate scalability in the context of M2T transformations.
2. To design algorithm(s) that will enable source-incrementality in M2T transformation languages.

3. To implement the source-incremental algorithm(s) in an existing M2T language.

4. To use the implemented source-incremental algorithm(s) to provide evidence that source-incrementality can be used to achieve scalable M2T transformations.

1.6 Research Scope

This section defines the scope and boundaries of this research work. As discussed in Section 2.3, there has been a lot of research into addressing scalability issues in MDE. Given the importance of model transformations, substantial effort has been devoted to addressing scalability problems in model transformations by improving the efficiency of the transformation processes through incremental transformations. However, research into incremental M2M transformation has received more focus than incremental M2T transformation. Despite the potential benefits modelling management processes (e.g., code generation) stand to gain from incremental M2T, less research attention has been directed at M2T transformation.

For reasons stated in Section 2.2.3, we believe that M2T and M2M transformations are fundamentally different and address different concerns. For instance, a typical M2T transformation produces unstructured artefacts, whereas, M2M transformations commonly produce other models which are structured. Therefore, incremental M2M techniques are unlikely to be optimal for M2T languages, and vice-versa.

In light of the above, this research is limited to providing source-incremental techniques that can be applied to M2T languages, and does not consider finding a general solution that can be applied to both M2T and M2M languages.

1.7 Research Methodology

To evaluate the validity of the hypothesis, a typical software engineering process was adopted. An initial analysis of incrementality in model transformation languages was followed by several iterations of design, implementation, and testing.

1.7.1 Analysis

The analysis phase entailed identifying recent M2T transformation languages, and commonly used M2T transformations in modelling tools which use M2T transformation (e.g., GmfCodegen is used to generate boilerplate code for graphical model editors).

Furthermore, during the analysis, experiments were performed to determine to what extent the identified M2T languages support incrementality, the results of which are discussed in Section 2.5.2.1. The results of the analysis have motivated the hypothesis and objectives of the thesis.

1.7.2 Design and Implementation

Following a successful analysis phase which led to the identification of the research challenges, the first phase of the design involved analysing the architecture of typical M2T transformation engines as specified in the MOFM2T RFP, which many M2T languages are based on, in order to identify common practical limitations which may have been imposed by the OMG specification. For example, most recent M2T languages are template-based. The design phase also included several iterations of devising new algorithms to provide with which M2T transformation engines can be extended to support incrementality. The design of each algorithm was followed by several modifications and improvements.

Given that the design was iterative, it followed that the implementation of devised algorithms was also iterative. The implementation involved analysing the architecture of a selected M2T transformation language which was then extended with the algorithms. For example, extending the transformation engine to enable transformation execution recording.

1.7.3 Testing

Similar to the design and implementation phase, testing occurred in several iterations, and tests were conducted immediately after the completion of each implementation instalment. In other words, testing completed a cycle of design-implement-test with several modifications preceding design activities. The tests were conducted using several case studies including real-life M2T transformations, and in some instances synthetic input models. The case-studies were varied in order to have a wide range of complex M2T transformations and ensure that limitations of the proposed incremental techniques are identified.

1.8 Thesis Structure

Chapter 2 presents a review of related literature. The review is structured into six sections. Section 2.1 presents a general overview of MDE and explores common terminology and technology that underpin model management processes. Section 2.2 discusses model transformations. Section 2.3 focuses on scalability concerns in MDE. In the context of model transformations, scalability issues arise as a result of evolving source models. As such, Section 2.4 presents an overview of software evolution, with respect to the cost and techniques for propagating changes across development artefacts. Section 2.5 reviews incremental model transformation and explores incremental techniques in M2M transformation. It also explores a research gap in the context of incrementality in M2T transformations. Finally, Section 2.6 explores incremental change propagation techniques in other areas of software engineering including compiler technologies, maintenance of materialized database views, etc.

Chapter 3 summarizes the reviewed literature in Chapter 2. From the reviewed literature, incrementality in the context of M2M transformations is largely solved following several years of research work in that context. Accordingly, Section 3.1 focuses on open research gaps (i.e., incremental change propagation) in M2T transformations. Section 3.2 discusses incremental transformation phases and techniques that can be applied at each phase.

Chapter 4 presents the *Signatures*, a novel technique for addressing the lack of support for source-incrementality in M2T languages. A signature is a template proxy that is derived from the evaluation of volatile parts of a template that is used to limit the re-execution of a M2T transformation to modified subsets of the source model. Section 4.1 presents a general overview of the signatures technique. Section 4.2 discusses the core concepts that underpin the signatures technique. It also discusses the way in which existing template-based M2T languages can be extended with support for signatures, and a prototypical implementation of signatures. Accordingly, Section 4.4 presents the implementation of the signatures method in an existing M2T language (EGL [11]). Lastly, Sections 4.5 and 4.6 conclude by summarizing the practicability, and the limitations of applying Signatures to M2T transformations.

Chapter 5 presents another novel technique (*Property access traces*) for enabling source-incremental transformations in M2T languages. Property access traces contain concise and precise information collected during the execution of a M2T transformation and can be used to detect which templates need to be re-executed in response to a set of changes in the input model(s). Section 5.1 presents an overview of the property access traces technique. Section 5.2 describes the major concepts that make up the property

access traces technique. Section 5.3 discusses the way in which an existing template-based M2T language (i.e., EGL) can be extended with support for property access traces. Section 5.4 describes the of property access traces in offline mode, that is, re-execution of a transformation only when reflection of changes is required in previously generated artefacts. Subsequently, Section 5.5 discusses the use of property access traces in online mode, that is, instant incremental change propagation. Section 5.6 discusses the differences between offline and online transformation executions using property access traces. Sections 5.7 and 5.8 discuss the limitations of property access traces, and summarizes the practicability of the technique.

Chapter 6 describes the strategy that is used to evaluate the effectiveness of source-incremental techniques. Specifically, Section 6.1 discusses the evaluation methods. The evaluation methods include testing whether an incremental M2T transformation engine possesses a set of established crucial properties (which are discussed in Section 3.1). Also, the evaluation method includes assessing the performance of an incremental transformation engine along two dimensions: runtime and space efficiency. Thus, Section 6.1 also presents and analyses three M2T transformation case studies which are used to perform empirical evaluation of the techniques proposed in this thesis. Having defined the evaluation methods and criteria, Sections 6.2 and 6.3 presents the evaluation of the proposed techniques in this thesis based on the evaluation criteria. It also discusses the results of the experiments performed on the case studies including the execution of our motivating example (i.e., INESS project). Finally, Section 6.4 provides further analysis of the results of the experiments, especially with respect to performance of the transformation engine which was extended with novel techniques proposed in this thesis.

Chapter 7 concludes by summarizing the findings and contributions of this research, and providing direction for further work in this area.

Chapter 2

Literature Review

This chapter presents a critical review of related work and current state-of-the-art of model transformation. Section 2.1 presents background study about MDE and focuses on terminologies and technologies that are commonly used in MDE. Section 2.2 reviews model transformations including the categories of model transformation, the underlying principles behind model transformations, as well as reasons they are considered an important model management process. Section 2.3 discusses current challenges in MDE with particular focus on the lack of support for the construction of scalable model management tasks. Specifically, it presents scalability as a major obstacle to the continued adoption of MDE in practice. Sections 2.4 presents a general overview of software evolution and discusses incremental change propagation between development artefacts in the context of MDE. Accordingly, Section 2.5 presents incremental change propagation using model transformations. Section 2.5.1 presents a critical review of incremental change propagation techniques in M2M languages. Section 2.5.2 explores the state-of-the-art of M2T languages with respect to support for incremental change propagation, and identifies a research gap in M2T transformation. Finally, Section 2.6 discusses common incremental change propagation techniques in other areas of software engineering.

2.1 Model Driven Engineering

Model driven engineering (MDE) is a software engineering approach in which models are the primary artefacts throughout the engineering process. In MDE, models assume more prominent roles than they do in traditional software engineering approaches, in which they are more often used for communication purposes. This definition is consistent with Mens's definition which describes MDE as a software engineering discipline

that relies on models as first class entities with the aim to develop, maintain and evolve software by performing model transformations [24]. MDE is based on a successful software engineering technique: raising the level of abstraction of software design specification [9, 25–27]. Higher levels of abstraction enable separation of system specification from implementation details and provide the following benefits: reduced development time and improved software quality achieved through the automation of repetitive development tasks (e.g., code generation, system verification, etc.) [26, 28]. In order to understand the benefits of MDE, we first need to explore its underlying principles and terminologies which include models and metamodels, model driven architecture, modelling platforms, languages, exchange format.

2.1.1 Metamodels and Models

Metamodels and models are the building blocks of MDE. In MDE, problem simplification or system abstraction is achieved through the use of models. A metamodel defines the abstract syntax of a modelling notation [29]. It captures the concepts of a domain, and based on the elements contained in the metamodel, a model is used to express a system in that particular domain. In essence, any model defined based upon the domain concepts captured in a metamodel must conform to the metamodel to be considered valid [30, 31]. Metamodels define semantics and constraints associated with domain concepts [32]. It is important to note that metamodels represent models as instances of some more abstract models. A metamodel is yet another abstraction which highlights the properties of the model itself. For example, consider figure 2.2, which is a minimal representation of a University domain. The model M in Figure 2.2 conforms to the metamodel MM shown in Figure 2.1, i.e., all elements in M are actually defined in MM. However, the definition of a model is not restricted to a single metamodel, a model can derive its elements from multiple metamodels.

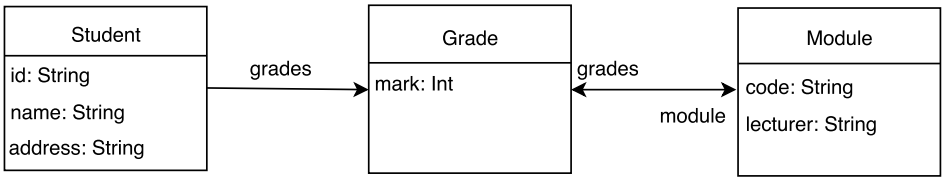


FIGURE 2.1: Example of a metamodel showing some university domain concepts

Models are described as the primary artefact of a development process on which other artefacts are dependent. A model is an abstraction of a system or its environment, or both. Models can also be regarded as abstract representations of the real world.

According to Cadavid, a model is a composition of concepts, relationships, and well-formedness [33]. Concepts describe the attributes of the domain being modelled. Relationships describe the connectedness of the concepts. Well-formedness describes additional properties that restrict the way domain concepts can be assembled to form a valid model. Bezivin describes a model as an abstraction of the real system which can be used to reason about the system and answer questions about it [34]. The usefulness of a model boils down to the extent to which it helps stakeholders take appropriate actions in order to reach and maintain a system's goal [24]. According to these definitions, it is clear that the primary purpose of models is to reduce system complexity through abstraction. MDE promotes this concept in that it allows developers to focus on the domain problem while minimal attention can be paid to the eventual underlying implementation technology by simplifying complex problems to reasonable extents.

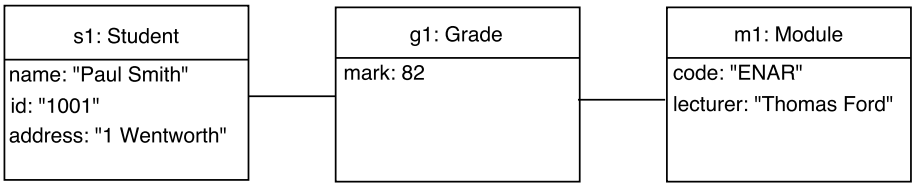


FIGURE 2.2: Example of a simplified university model that conforms to the metamodel in Figure 2.1

2.1.2 Modeling Languages

In software engineering, modelling languages are usually oriented to describing orthogonal aspects of a system through different sets of symbols and diagrams, so as to reduce the risk of misunderstanding. The standard metamodeling language defined by the OMG is MOF. However, Ecore, the metamodeling language of EMF has become the de-facto standard primarily because it is tailored to Java for implementation and the Eclipse platform which has a huge user base [29].

A modeling language is made up of three parts:

- *Abstract syntax* describes the structure of the language and the way different primitives can be combined together, independent of any particular representation or encoding.
- *Concrete syntax* describes specific representations of the modeling language, covering encoding and/or visual appearance issues. The concrete syntax can be either textual or graphical. It is what the designer usually looks up as a reference in modelling activities.

- *Semantics* describes the meaning of the elements defined in the language and the meaning of the different ways of combining them.

There are 2 broad categories of modeling languages: General Purpose Modelling Language (GPML) and Domain Specific Modeling Language (DSL). DSMLs are designed for specific domains (e.g., online financial services, avionics, warehouse management, etc.), context, or company to ease the task of people that need to describe elements in that particular domain. Examples of DSMLs include SQL for relational databases, VDHL for hardware description languages, HTML for web development. A DSML captures all the elements necessary to construct models in specific domains. These elements are a metamodel, a graphical or textual representation of concepts specified through metamodel, the semantics associated with the domain concepts [33]. In contrast to DSLs, GPMLs represent tools that can be applied across multiple domains for modelling purposes. For example, UML, Petri-nets or state machines.

2.1.3 Model Driven Architecture (MDA)

The MDA is an open vendor-neutral approach to developing complex systems which are prone to business and technological changes. It defines standards for: models and modeling languages; representing and exchanging models (XMI); specifying constraints (OCL); specifying transformation on models [35]. MDA is a framework based on the UML and other industry standards for visualising, storing and exchanging software designs and models. It allows developers to build systems based on their knowledge of the core business logic and data without much consideration for the underlying implementation technology. It encourages the creation of models at different levels of abstraction, persisted in standard formats such as XMI[1].

As shown in Figure 2.3, the MDA stack is comprised of 4 levels of abstraction; M0 representing real world objects; M1, the model level contains instance objects whose classes are defined in M2, and finally, there is M3 the highest level of abstraction which is a meta-metamodel.

2.1.4 MOF – Meta Object Facility

OMG's MOF is a semi-formal approach to defining models and metamodels. It was developed to provide a standard metamodeling language and enable systematic model/metamodel interchange and integration [36]. As such it sits at the top of the four-tier

[1] http://en.wikipedia.org/wiki/XML_Metadata_Interchange

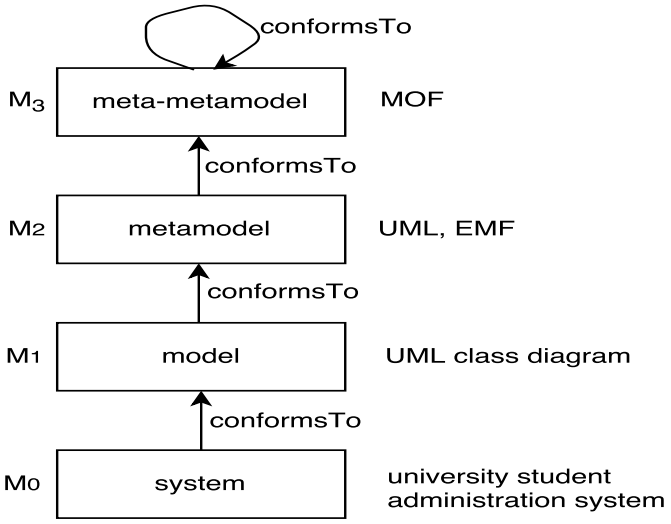


FIGURE 2.3: MDA's layers of abstraction [1]

MDA stack. MOF was introduced because of the need to have a standardized metamodel across the software development landscape [33].

2.1.5 EMF – Eclipse Modeling Framework

EMF[2] is a framework that enables the definition of metamodels and instantiation of models conforming to the defined metamodels. The metamodels are defined using Ecore metamodeling language. Ecore is an implementation of EMOF. Like MOF, Ecore sits at the M_3 level of the MDA stack (Figure 2.3). EMF brings modeling to Eclipse and is fast becoming the de-facto standard for Eclipse based modeling tools [37]. In EMF metamodels are defined using the Ecore metamodeling language. The EMF model is a specification of the data model which can take any of the following forms: UML class diagrams, XML Schema [38]. Figure 2.4 represents a high level overview of Ecore. In Ecore every object is an *EObject*. However, the root element of an Ecore metamodel is an *EPackage*. Other metamodel elements include *EDataTypes*, *EClasses*, *EAttributes*, *EReferences*. The Ecore model consists of the following key concepts: [2]

- EClass models entities in a domain. Classes are identified by name and usually contain any number of features, i.e., EAttributes and EReferences. For example, a Student class in the metamodel (Figure 2.2) has a 'name' attribute and a reference to a Module.

[2]http://eclipse.org/modeling/emf/

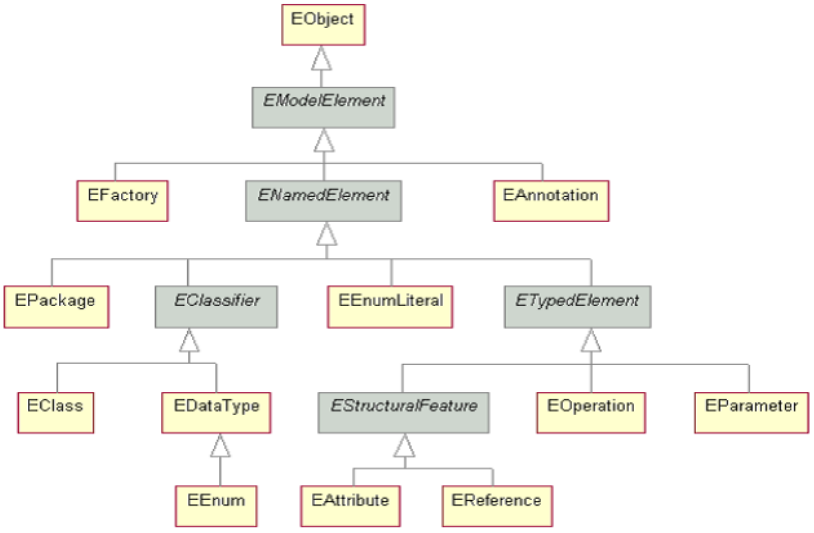


FIGURE 2.4: Part of Ecore Metamodeling Language taken from [2]

- EAttribute models attribute of an EClass. It represents the leaf components of instances of an EClass's data. EAttributes are identified by name and have a data type.
- EReference models associations between classes. Associations can be bidirectional with a pairing opposite reference. A stronger type of association called containment is also supported, in which a class contains another.
- EDataType models simple types and acts as a wrapper which denotes primitive or object types. It represents the type of an attribute.

2.1.6 XMI - XML Metadata Interchange

Given that there exists a number of different technical spaces (XML which uses XML Schema as meta-metamodel, MDA which uses MOF as its meta-metamodel), it is pertinent that there also exists a standardised mechanism for modeling frameworks and tools to interoperate or exchange data in order to bridge technical spaces [39]. OMG's response to this need was the creation of XMI, which was designed to enable tool interoperability. For example, a UML model in XML format created using a UML modeling tool can be parsed into an XMI document which can then be imported into a different modeling tool.

2.1.7 Epsilon - Extensible Platform of Integrated Languages for Model Management

Epsilon is a model management tool for analysing and manipulating models in specific ways [23]. It features a host of task-specific languages for different model management operations. For example, EOL (Epsilon Object Language) is used for direct model manipulation, including creating new models, querying, updating, and deleting model elements [40]. EOL also forms the core of other languages in the Epsilon suite of languages. Other Epsilon languages include:[3] ETL (Epsilon Transformation Language), for model-to-model transformation, EGL (Epsilon Generation Language), for model-to-text transformation, Flock used for model migration.

2.2 Model Transformations

Model transformation is the process of translating one model (*source*) to other representative forms (typically, another model (*target*)). Model transformation has been characterized as the heart and soul of MDE [10]. Model refactoring, merging, weaving, code generation from models, etc., would not be possible without transformation theory and tools [10, 41]. Model transformations are applied in MDE to serve various purposes which include model quality enhancement, expression of platform-independent models as platform-specific models, automating software evolution, identifying software patterns, reverse engineering models, etc [42].

Model transformation specifications are most often defined through a set of transformation rules. Transformation rules declaratively specify how source metamodel types are mapped to corresponding target metamodel types (see example in Listing 2.1). Many transformation languages derive their expressiveness from OCL (Object constraint language). OCL enables formal specification of model properties in expressive formats [43]. Mappings between source and target model elements are expressed in OCL-like expressions. A transformation specification can contain multiple rule definitions. Many transformation languages have mechanisms for controlling the execution order of rules, referred to as rule scheduling. Rule scheduling can be implicit or explicit [44]. Implicit rule scheduling relies on automatic realisation of relations between rules. Explicit scheduling allows manual specification of rule execution order.

Model transformations can be classified by the types of target produced by the transformation. A transformation can produce a target which is a model or produce a target

[3] http://www.eclipse.org/epsilon/doc/book/

that is textual. When the target of a model transformation is a model, the transformation is a model-to-model transformation (M2M). On the other hand, when the target produced from a transformation is textual in nature, then it is a model-to-text transformation (M2T).

2.2.1 Model to Model Transformation (M2M)

M2M transformation is the process of transforming a model to a different model representation. That is, the transformation translates elements in a source model M_s which conforms to a metamodel MM_s to equivalent elements in a target model M_t that conforms to a metamodel MM_t. Figure 2.5 is a simplified example of a model to model transformation. In this example, the Student metaclass is mapped to a Transcript, and a Grade to a TranscriptItem.

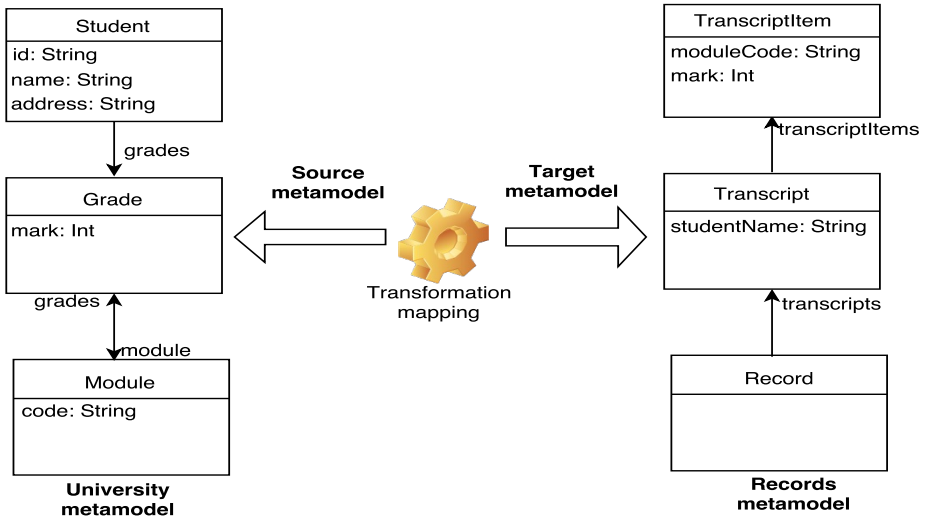


FIGURE 2.5: Example of a Model-to-Model Transformation

M2M transformations can be categorised in two [24]: 1. Endogenous, 2. Exogenous. Endogenous transformations take place when some re-factoring is done on a source model producing a target model which is essentially another instance of the source model. In other words, the transformation traverses and manipulates the source model. On the other hand, exogenous transformations are executed on a distinct source model and produces a distinct target model. Exogenous transformations are commonly used to synchronise two input models (i.e., source and target), especially after changes have been applied to any of the models.

2.2.1.1 Transformation Language Technologies

Given the central role model transformation plays in MDE approaches generally, it is important to understand the technology that transformation languages are built upon.

Query View Transformation - QVT

QVT was developed as the standard transformation language by the OMG [45]. The aims of the language include providing a mechanism for querying MOF-based models, creation of views from models, creation of expressive definition of transformations, hence the name Query, View, Transformation [46]. A query is an expression that is evaluated over a model. The result is one or more instances of types defined in the source model. A view is a model which is completely derived from another model. A transformation is the generation of target model(s) from source model(s) based on defined transformation which can contain a number of rules.

There are two parts to the QVT language. A declarative part which is made up of relational and core languages. The relational language enables complex pattern matching over input models [47]. On the other hand, the core language enables pattern matching over a primitive set of variables. The imperative QVT language, otherwise called QVT Operational enables implementation of transformation rules that are not applicable in a relational language.

Triple Graph Grammars - TGG

TGGs declaratively define the relation between two models [45]. In addition to source and target models, they define a correspondence model which serves as a mapping between source and target model elements such that an Object in the corresponding model is made up of at least one source model element and target model element. Graph transformation rules match left hand side model elements with corresponding right model elements. Graph-based transformations are commonly implemented in M2M languages (e.g., VIATRA [48]) because they allow explicit specification of transformation [49]. Unlike QVT based transformation languages TGG supports bidirectional transformations [50].

2.2.1.2 Specification of a Model-to-Model Transformation

A M2M transformation comprises of transformation definition, transformation rule(s), source and target models. A transformation definition is a set of transformation rules. Transformation rules define how specific set of source model elements are to be mapped

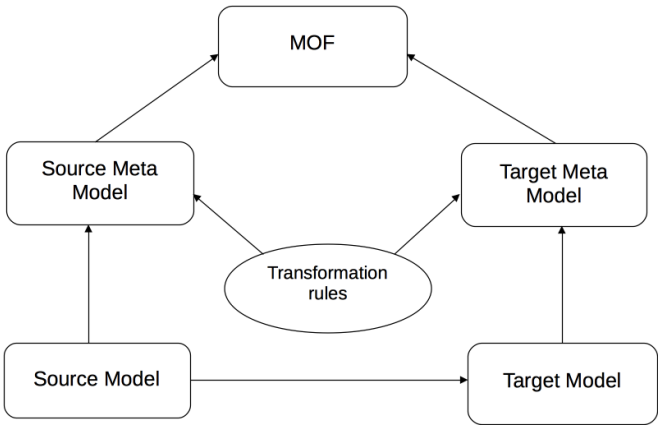


FIGURE 2.6: Overview of Model Transformation Process taken from [3]

to equivalent set of target model elements [51]. Figure 2.6 captures a typical M2M transformation.

- The transformation process involves having a source model that conforms to one or more source metamodels. Most transformation tools will automatically check the conformance of the source model to its metamodel before running transformation rules on it.
- The transformation engine reads the source model.
- The transformation engine executes the transformation rules.
- The transformation engine having applied the rules to the source model elements, writes to the target model.

Listing 2.1 is an example of a M2M transformation specification that is based on the metamodels described in Figure 2.5.

```
1  rule Grade2TranscriptItem
2    transform g: University!Grade
3    to t: Records!TranscriptItem {
4      t.moduleCode = g.module.code;
5      t.mark = g.mark;
6    }
```

LISTING 2.1: M2M transformation definition based on Figure 2.5 specified in ETL

In this transformation, a rule is defined which translates each object of metaclass Grade in a model that conforms to the University metamodel to a corresponding object of metaclass TranscriptItem in a model that conforms to the Records metamodel. A TranscriptItem object derives its properties (i.e., moduleCode and mark) from a Grade object.

There are three types of M2M transformation language styles: declarative, imperative, and hybrid [24].

- *Declarative* languages express mappings between source and target model elements using mathematical relations. They are usually easy to use because they execute in a black box manner, i.e., they automate model traversals, rule execution scheduling [52]. There are two types of declarative languages: relational and graph transformations. As the name implies, relational transformation languages are based on relations between source model elements and target model elements. On the other hand, graph transformation languages express mappings between source and target model elements through graph patterns [53].
- *Imperative* languages explicitly specify how transformations are performed. They can be applied to more complex transformations where there is need for imperative manipulation from an executable language [51].
- *Hybrid* languages are a combination of declarative and imperative approaches. They leverage the expressiveness and conciseness of the declarative style and through imperative characteristics enable the execution of complex transformations. Examples of such hybrid transformation languages include Atlas transformation language (ATL) [54], Epsilon transformation language (ETL) [55].

2.2.1.3 Model-to-Model Trnasformation Languages

ATL. Atlas Transformation Language is designed as a hybrid transformation language containing a mixture of declarative and imperative structures [54]. The declarative features of ATL allows matching of source to target model elements while its imperative features enable more complex operations e.g., creation of model elements. There are two types of declarative rules in ATL: matched and lazy. Matched rules are automatically executed on the input model while lazy rules are explicitly called from another rule as specified by the transformation developer.

ETL. Epsilon Transformation Language is a hybrid transformation language [55]. It uses its imperative constructs which are similar to the imperative programming language features (e.g., loops, variables) for complex transformations. Its imperative features are based on Epsilon's object language (EOL) [40]. In addition, ETL supports transformation execution on models defined using different metamodeling technologies. This is achieved through Epsilon's model connectivity (EMC [56]) layer which serves as a common interfacing facility for diverse modeling technologies e.g., EMF, MDR,

XML, etc. ETL transformations are organised into modules. Each module contains transformation rules which expresses how source model elements are translated into target model elements.

VIATRA. VIATRA is a graph-based model transformation language. It employs mathematical relations to specify precise rule based graph transformation definitions, and it uses abstract state machines to manipulate models [57]. Execution flows of transformations are expressed as state machines. It offers advanced constructs for performing recursive graph traversals and multi-level metamodeling.

Tefkat. Tefkat is a QVT-based declarative model transformation language [52]. A Tefkat transformation specifies a set of constraints over a set of source and target models. The constraints are evaluated to determine how the source model elements are mapped onto equivalent target model elements. For example, a constrain might be used to determine whether an equivalent of a source model element already exists in the target model.

XTend. XTend is an imperative model transformation language, and it is one of oAW's (OpenArchitectureWare) [58] suite of model management languages. oAW is a modeling platform for defining and manipulating models. Transformations rules implemented in XTend declare imperative sections which contain expressions for translating model elements [59]. Given its imperative nature, rule expressions can be chained (the result of each execution piped into the next from left to right), and execution order has to be explicitly specified by the transformation developer.

2.2.2 Model-to-Text Transformation (M2T)

Model to text transformation is an important model management process of generating text (e.g., application code) from models [11, 60]. However, with M2T transformation, as defined in [61], generation is not limited to code: the transformation process can produce any kind of textual artefact including documentation, requirements specifications, manuals etc., because the generated text is independent of the target language. Unlike M2M transformation, the targets of M2T transformations are textual, and most often of arbitrary structure which do not conform to any metamodel.

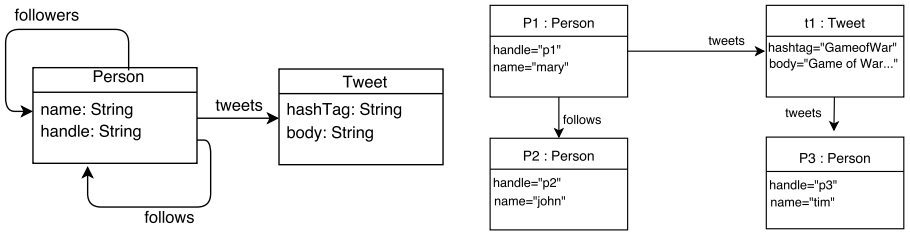
There are two categories of M2T transformations:

1. Visitor-based: This approach entails providing a visitor mechanism to traverse the internal representation of a model and write text to a stream [62, 63]. An example of such visitor-based language is Jamda [64]. Jamda represents UML models with a set of object classes. Through dedicated APIs (e.g., Java metadata interface [65]), it can access and manipulate models, while it employs a visitor mechanism to generate text.

2. Template-based: Templates are text files which represent the eventual output of a model-to-text transformation which contain placeholders. The placeholders represent variables that are to be filled with data fetched from the source model. Text templates are usually made up of static and dynamic sections. As seen in 2.2, static sections contain text that is written verbatim as part of a transformation output and dynamic sections contain sections with the place holders. The dynamic sections are also enclosed in special command tags (e.g [% %], <% %>). In contrast to the visitor-based approach, the structure of a template resembles closely the syntax of the target language. The majority of recent M2T languages support template-based text generation.

2.2.2.1 Template-based M2T Transformation Execution

A M2T transformation is specified using a *Module*, which comprises one or more *Templates*. A *Template* comprises a set of *Parameters*, which specify the data on which a template must be executed; and a set of *Expressions*, which specify the behaviour of the template. In addition to the typical types of expression used for model management (e.g., accessing or updating the properties of a model element, iterating over associated model elements, etc.), M2T transformation languages provide two further types of expressions: *TemplateInvocations*, which are used for invoking other templates; and *FileBlocks*, which are used for redirecting generated text to a file. A *TemplateInvocation* is equivalent to in situ placement of the text produced by the *Template* being invoked.



(a) Metamodel. (b) Model.

FIGURE 2.7: Example model of a social network.

Consider, for example, the M2T transformation in Listing 2.2, which produces sections of *HTML* pages of the form shown on the right-hand side of Figure 2.7. This M2T transformation comprises three templates: *generateSections* (lines 3-10), *personToDiv* (lines 12-25), and *tweetToDiv* (lines 27-34). All of the templates accept one parameter (a *Network* object, a *Person* object and a *Tweet* object, respectively). The first template invokes the second (third) template on line 5 (line 8) by passing an instance of Person (Tweet). Note that the second and third templates both redirect their output to a file named after the *Person* or the *hashtag* of the *Tweet* on which they are invoked (lines 13 and 28).

```
1  [module generateHTML(Netwrok)]
2
3  [template public generateSections(n : Network)]
4  [for (p : Person | t.persons)]
5  [personToDiv(p)/]
6  [/for]
7  [for (t : Tweet | n.tweets)]
8  [tweetToDiv(t)/]
9  [/for]
10 [/template]
11
12 [template public personToDiv(p : Person)]
13 [file (p.name)/]
14 <div>
15   <p>Number of followers: [p.followers->size()/]</p>
16   <p>Number of following: [p.follows->size()/]</p>
17   <h2>What's trending?</h2>
18 [for(f : Person | p.followers)]
19   [for(t : Tweet | f.tweets)]
20     [t.hashtag/]
21   [/for]
22 [/for]
23 </div>
24 [/file]
25 [/template]
26
27 [template public tweetToDiv(t : Tweet)]
28 [file (t.hashtag)/]
29 <div>
30   Hashtag: [t.hashtag/]
31   Re-tweeted [t.retweets->size()/] times
32 </div>
33 [/file]
34 [/template]
```

LISTING 2.2: Example of a template-based M2T transformation, specified in OMG MOFM2T syntax.

2.2.2.2 Specification of a Model-to-Text Transformation

Execution of a M2T transformation specification (i.e., a *Module*) is performed by a transformation engine. A transformation engine takes as input a source model and a *Module*, and outputs text. Execution begins by creating a *TemplateInvocation* from an initial *Template* and *Parameter Values*. The *TemplateInvocation* is executed by evaluating the expressions of its *Template* in the context of its *Parameter Values*. During

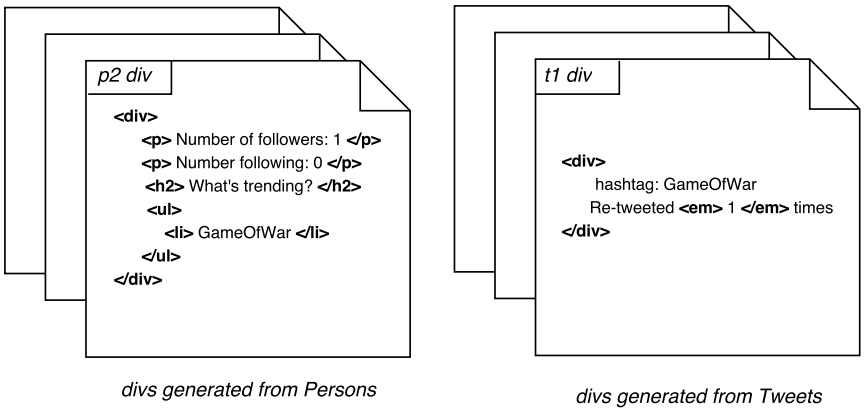


FIGURE 2.8: Example outputs of executing the transformation in Listing 2.2 on the input model in Figure 2.7(b).

the evaluation of a *TemplateInvocation*, additional *TemplateInvocations* can be created and evaluated in the same manner, and any *FileBlocks* are evaluated by writing to disk the text generated when evaluating the expressions contained within the *FileBlock*. For example, execution of the of the M2T transformation in Listing 2.2 would proceed as follows:

1. Load the source model.
2. Create and evaluate a *TemplateInvocation* for the primary template, *generateSections* (see line 1), passing the only *Network* object in the source as a parameter value.
3. For each of the *Person* contained in the *Network*:
   (a) Create and evaluate a *TemplateInvocation* for the *personToDiv* template, passing the current *Person* object as a parameter value.
   (b) Emit html text for the person div (lines 14-24) to a text file with the same name as the *Person*.
4. For each of the *Tweets* contained in the *Network*:
   (a) Create and evaluate a *TemplateInvocation* for the *tweetToDiv* template, passing the current *Tweet* object as a parameter value.
   (b) Emit html text for the tweet div (lines 29-32) to a text file with the name of the file set to the *hashtag* of the *Tweet*.

2.2.2.3 M2T Transformation Languages

Template Transformation Toolkit (T4). A T4 text template like many other template languages is a mixture of text blocks and control logic that generate any form of textual artefact from models[4]. The generation engine of T4 is largely dependent on the .NET framework and languages [66]. Thus, the control logic is written as fragments of program code in Visual C# or Visual Basic. The T4 template engine can generate any type of textual artefact. T4 transformations are executed on UML-based models. One key shortcoming of T4 is that it does not support the idea of mixing generated code with user-written text.

The run-time environment allows the developer to embed Visual Studio statements (e.g., *<#= DateTime.Now #>*) in the template, which are executed when the transformation is run. In addition, T4 supports instantiation of objects defined in the other files (e.g .cs files) in the project space, in the same manner they would be accessed in non-template files.

Acceleo. Acceleo is based on three separate components: the compiler; the generation engine; the tooling. It is capable of reading any model produced by any EMF-based model. A transformation written in Acceleo is made up of modules, source model(s) and target files. A module can consist of several templates describing necessary parameters to generate text from models. A main template serves as the entry point of the transformation execution and is indicated by the presence of a *@main* at the top of the template's body.

Epsilon Generation Language (EGL). EGL [11] inherits concepts and logic from EOL (Epsilon Object Language) [40]. EGL is a M2T language developed at the University of York. It is the text generation language of Epsilon's suite of model management languages. At its core lies a parser which generates an abstract syntax tree comprising static and dynamic output nodes for a given template. Unlike Acceleo, the EGL transformation engine has a dedicated transformation rule execution coordination mechanism (EGX). In addition to coordinating rule execution, EGX enables the generation of multiple files from a single template.

```
1 rule Student2Transcript
2   transform s : Student {
3     template :'record.egl'
4     target : s.name + '.txt'
5   }
```

LISTING 2.3: EGX example

[4]http://msdn.microsoft.com/en-gb/library/vstudio/bb126445.aspx.

It inherits its imperative constructs from EOL, provides data types which are similar to Java's and supports user-defined methods on metamodel types.

Xpand. Xpand is a statically typed template language whose main features are aspect oriented programming, model transformation and validation[5] with some limitations on types of operations it can perform. It also logs link information between source and target elements in between code generations.

MOFScript. MOFScript was an initial proposal to the OMG for their model-to-text RFP, which was developed by Sintef and was supported by the EU Modelware project. MOFScript was developed in response to the need to standardize M2T transformation languages. It works with any MOF-based model e.g UML, RDBMS, WSDL, BPMN etc., and it is heavily influenced by QVT. A MOFScript transformation is composed of one or more modules, with each module containing transformation rules. A MOFScript rule is a specialisation of QVT-Merge operational mappings and MOFScript constructions are specialisations of QVT-Merge constructions [67]. Transformations can be imported and re-used by other transformations.

Java Emitter Templates (JET). JET can be used to generate text from EMF-based models. It creates Java implementation classes from EMF models. The Java implementation classes are then used to write text output. The implementation class has a 'generate' method used to obtain string result. In other words, the transformation is from Java objects to text. Command tags in JET are called scriplets, denoted by $< \%\% >$, they can contain any Java code[6]. Unlike EGL and Acceleo, JET does not support models implemented using MOF.

Velocity. The Velocity projects by Apache include: Velocity Engine[7] which is a templating engine that allows a template language to reference objects defined in Java code. Velocity transformation language (VTL) is written in Java enabling easy embedding in other Java applications. Velocity makes use of XML transformations. Velocity templates extract data from XML files which are used in generating text files. The generator is created by implementing Java classes called descriptors representing each node in the XML file.

[5] http://www.eclipse.org/modeling/m2t/?project=xpand
[6] http://www.vogella.com/articles/EclipseJET/article.html
[7] http://velocity.apache.org/engine/releases/velocity-1.7/

Freemarker. Freemarker[8] is a template language that is based on Java. It was designed specifically for generating web pages. Like Velocity, it has minimal programming capabilities. Thus, it also requires Java programs to prepare the model data.

2.2.2.4 Overview of a M2T Module in EGL.

In the previous sections, we provided a general overview of template-based M2T transformations are defined, and described some common template-based M2T languages. In this section we describe how a modern M2T transformation language implements a model transformation module from a transformation execution perspective. Hence, this section discusses the way in which a M2T transformation engine might implement mechanisms for coordinating rule invocations and for directing transformation output to file. The rest of this section describes the implementation of a transformation *Module* in EGL.

Figure 2.9 represents an overview of the implementation of a M2T transformation in EGL. The transformation engine emits the contents of static sections verbatim (does not require applying any logic) while text emitted from the dynamic sections are the result of logic operations, and performing model queries. The *dynamic output buffer* is responsible for outputting text generated from dynamic sections while the *static output buffer* holds text from the static sections of a template. An instance of a *RuleInvocation* is the execution of a template on a specific model element. *RuleInvocations* have context types which indicate the type of a model element on which a transformation rule can be invoked. In a typical EGL transformation, each instance of a created *RuleInvocation* is executed on only one model element, and generates a single file.

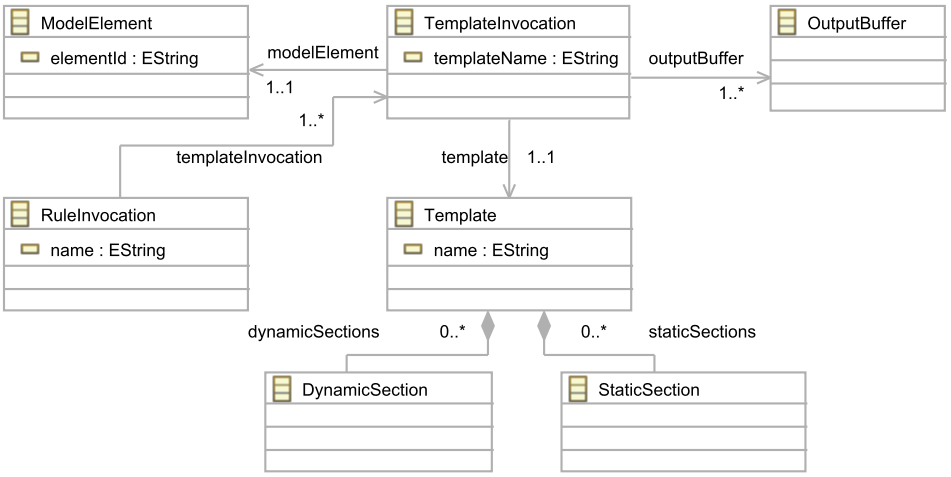


FIGURE 2.9: Module invocation in EGL M2T Language.

[8] http://freemarker.sourceforge.net/docs/

```
pre {
  var cssClass = "gold";
}

rule personToDiv
  transform aPerson : Person {
    guard: aPerson.followers.size() > 0;

    parameters {
      var params : new Map;
      params.put("cssClass", cssClass);

      return params;
    }

    template : "personToDiv.egl"
    target : aPerson.handle + ".txt"
}

rule tweetToDiv
  transform aTweet : Tweet {
    guard: aTweet.retweets.size() > 0;

    parameters {
      var params : new Map;
      params.put("cssClass", cssClass);

      return params;
    }

    template : "tweetToDiv.egl"
    target : aTweet.hashtag + ".txt"
}
```

LISTING 2.4: Example of an EGX M2T program

In general, M2T transformation processes do not end at the generation of text but require a further step of writing the generated text to files. Most M2T languages provide mechanisms for writing generated text to files and manipulate the local file system. EGX is a recent extension to EGL that provides a co-ordination mechanism for directing the output of executing templates to files. An overview of a transformation execution using EGX is shown in Figure 2.10. The contents and destination of generated files are determined at runtime. Listing 2.4 shows a typical EGX transformation module which is equivalent to the MOFM2T module earlier described in Listing 3, but contains additional *pre* and *post* blocks. An EGX module can comprise any number of transformation rule blocks, a *pre* and a *post* block. A transformation rule block defines how an input model element can be transformed into fragments of text contained in a generated file. Each transformation rule block also specifies the context type which indicates the type of model elements a rule can be invoked upon. In addition, a transformation rule block also includes expressions that define other properties of the transformation (e.g., template, guard, target, parameters). The template expression returns the EGL template on which the rule is to be invoked; the guard is a constraint which returns a boolean and limits the application of the rule to the conditions specified in the guard expression; the target expression is resolved to the name

and destination of the generated file; parameters is a collection of variables consumed by the transformation during the execution of a template. A *pre* block contains statements that must be executed before rule invocations and typically define variables that are passed to the transformation engine when a template is executed. A *post* block on the other hand contains instructions (e.g., pretty print directive) that are executed after the transformation engine might have finished executing templates.

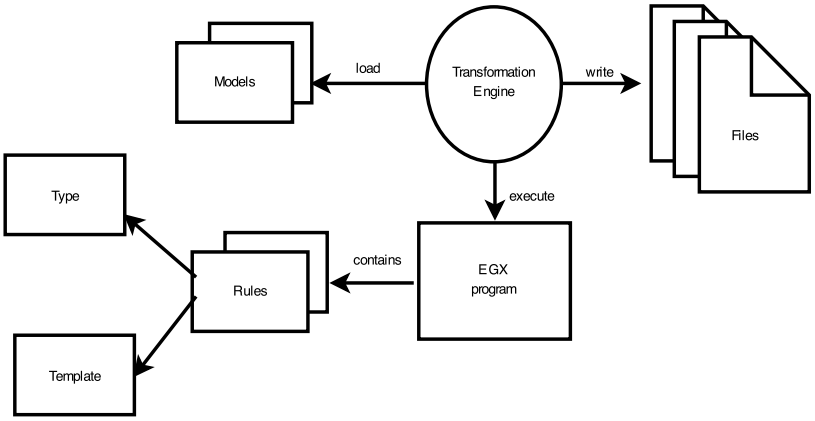


FIGURE 2.10: Overview of transformation execution using EGX.

2.2.3 Discussion

M2M and M2T transformations are based on the same principles and are employed to achieve similar goal. For example, they are used to translate source models to other dependent artefacts. Both take as input, models and some specification of transformation rules. Despite their similarities, they differ in implementation, and as such have different concerns from a research perspective. Notably, most M2T transformations specifications are template based. Templates contain executable code written in the transformation language which are often imperative and computationally complete in order to perform complex calculations on models and other input parameters. M2T transformation engines also possess mechanisms for manipulating strings, escaping special text delimiters, whitespace handling, and writing text to files. On the other hand, M2M transformations are often specified in blocks of declarative code that explicitly maps source model elements to corresponding target elements. Although a subset of M2M transformation languages support imperative constructs, they do not handle some of the unique requirements of M2T languages e.g., parsing texts or redirection of generated text to files.

2.3 Scalability in MDE

Software engineering continues to witness a rise in levels of abstraction introduced into system design as a result of growing complexity of software systems. MDE as a software engineering discipline promotes this trend and promises improved productivity and better quality software [69]. Although the past decade has seen increasing numbers of industry practitioners adopting MDE techniques, further adoption of MDE is stymied by scalability concerns. Scalability is a major stumbling block to the adoption of MDE [70]. For example, as model sizes increase, MDE techniques such as model transformation, validation, do not scale because some of the existing modeling tools cannot operate on large models without noticeable degradation in performance. In a study on the experiences of industry practitioners on their use of MDE, Mohagheghi et. al. [71] identified that often the lack of scalable model management operations was a prominent concern in industry.

Kolovos et. al. [72] identified three aspects in which the lack of scalability in MDE poses challenges to both the academic community and industry: 1. managing volume increase, 2. collaborative work, and 3. incremental change propagation. With respect to managing volume increase, as models grow from containing hundreds of model elements to containing millions of model elements, it is important that modeling tools scale accordingly. For example, facilities for persisting large models should be robust enough to support efficient persistence of models (following model modification or creation) regardless of the size of the models.

A related concern of the lack of capacity of modeling tools to cope with large, evolving models is that it discourages collaborative work. According to Bergmann et. al., scalability challenges prevent collaborative work, and represent a prominent threat to MDE adoption [73]. As with traditional software engineering approaches, in MDE, the ability of development teams to access and work on the same set of development artefacts while the consistency of such artefacts is not compromised is important. However, the lack of mature tools and infrastructure which will enable large model persistence and efficient access (read and write) to models can hamper collaboration among developers. Especially considering that in a typical software engineering environment, different developers may need to access and modify the same models.

In the context of model transformations, typical concerns of industry practitioners are captured in statements such as [72]:

1. *I would like to use model transformation. When I make a small change in my large source model, it is important that the change is incrementally propagated*

to the target model. I don't want the entire target model to be regenerated every time.

2. *I use code generation (M2T). However, when I make a small change in my large source model, I don't want all the code to be regenerated.*

In light of these statements, it is apparent that scalability concerns arise as a result of evolving software. Since in MDE models are considered primary artefacts of the development process on which other development artefacts depend, changes often initially emerge from source models. As such, when models evolve, other dependent artefacts have to evolve accordingly. To tackle the issue of scalability, MDE tools need to support incrementality [26] or efficient propagation of changes in a manner that reduces redundant re-computations. The question or challenge is how can these changes be propagated across artefacts in an efficient manner. In the context of model transformations, this challenge has been the subject of much research. However, much of this research has been on incremental M2M transformations while very little has been on incremental M2T.

Reactive model query and transformation have been recommended as a research direction to tackle scalability issues in model transformations [74]. Research in this direction is published in [73] by Bergmann et. al. They focus on managing model evolution in the context of inter-related MDE development tasks in a single workflow on an industrial scale. For instance, a workflow might include verification of models using OCL constraints, M2M transformations, M2T transformations, design rule validation, etc. In such workflows, it is desirable that all model management tasks can be incrementally executed when underlying source models evolve. Considering the inter-dependencies among the model management tasks, the execution of one task might interfere with the execution of others. Therefore, incremental re-synchronization of the source models with other development artefacts (produced by different tasks) requires careful consideration. For example, the re-execution of an endogenous M2M transformation can invalidate the results of an incremental verification of the source model. As such, they suggest a reactive transformation framework that is based on the reactive programming paradigm [75]. The framework triggers re-execution of relevant model management tasks in the correct sequence (to limit interference) as changes occur in the source model.

Before reviewing literature regarding incremental change propagation through model transformation, a more general overview of software evolution is needed. This is essential to understand what factors are responsible for software evolution, the costs associated with it, along with common software evolution techniques, and how all these relate to software evolution in MDE.

2.4 Software Evolution

Software evolution can be described as any software development activity that necessitates the propagation of changes from one or more development artefacts to other dependant artefacts, in order to ensure consistency across all artefacts of the software development process. Change propagation is central to software evolution, and it can be described as the changes required to other entities of a software system to ensure a consistent view of the software system after changes are applied to particular entities of the software system [76]. In empirical studies [77–79] of software evolution, as much as 70% of software development effort is reported to be devoted to software evolution activities.

Given the importance of software evolution, it has been the subject of much research work. According to one of the software evolution laws introduced by Lehman [80] in 1970, actively used software systems must continually change to accommodate new requirements of its stakeholders. The chief factors responsible for software changes are [78, 81]:

- Changing user requirements.
- Changing technology.
- Changing organisational culture.

Rarely do software life cycles end at deployment; there are several activities that are on-going so long as the software remains in use. These include providing bug fixes, patches, adding new features, etc. According to a study of 8000 projects reported by the Standish Group, modifications applied to the projects were as a result of changing user requirements [81]. 75% of changes to software are due to changing development environments and emergence of new user requirements [13]. Most software development work is primarily focused on enhancing and adapting existing system. Commonly, software undergoes evolution in order to keep it up-to-date with continuously evolving customer needs [82].

With such enhancements come increased system complexity and costs [83]. Kemerer observes that there is a direct correlation between software complexity (considering software size, modularity, branching) and maintenance costs [84]. Accommodation of changes to software comes at huge costs – analysis of required change and its impact, implementation of the change. Costs associated with software evolution are not limited to these. Revalidation and testing are additional important activities which are necessary to prevent introduction of bugs into the system. Every evolution of a system

can result in a cycle of analysing the new requirements, performing an impact analysis of the changes required, revalidation of the system, and testing. The cost imposed by software evolution activities is aptly captured by Sommerville's description of software evolution as a necessary expensive process that requires a lot of time to locate places where components need to change or affected by a change to another component, time consuming efforts to implement and test the software [16, Chapter 21].

Often, much of the costs associated with software evolution are as a result of performing redundant activities during change propagation. For instance, every time a change is applied to a component of a software system, performing complete system tests when unit tests will suffice, will incur unnecessary computation cost, potentially waste development time, and erode the efficiency of the development process. This is commonly referred to as batch processing in software engineering.

An alternative approach is incremental change propagation. Incremental change propagation processes are restrictive (i.e., only changes and the components affected by the changes are considered during change propagation) and can result in more efficient development process. Incremental change propagation plays an essential role in software evolution, particularly in an agile environment [85, 86]. Section 2.5 will elaborate on incremental change propagation and how it has been applied to improve efficiency in several aspects of software engineering including compiler, relational databases, etc.

2.4.1 Software Evolution Techniques

The previous section provided the taxonomy of software evolution, and this section will discuss common techniques used to manage software evolution. While software evolution can be classified according to various factors (e.g., the cause of the change, when the change occurred, etc.), a common characteristic of all types of change is that other activities are initiated in response to changes. Typically, the process of addressing software change will involve the following activities [12]:

Change identification. This can be very helpful in addressing changes to software especially when the change is only first obvious in one of the software development artefacts. For example, Linux's "make" utility is used to automatically detect which parts of C/C++ programs have been modified by comparing the timestamps of the source files against the timestamps of object files.

Impact analysis. Impact analysis is an evaluation of how changes would affect the internal consistency of an evolving system, and other associated systems or sub-systems

and identification of modifications necessary to preserve the consistency of the system. It is the process of determining the effect a change is going to have on a system [87]. Having identified what has changed in a system or what needs to be changed, the next thing is to identify what impact this change will have on other parts of the system, and propagate this change to the identified parts. In the example of the make utility, the compiler selects which source files that need to be re-compiled based on the timestamps of the source files and the object files. This kind of mechanism saves a lot of re-compilation time particularly for large projects. The importance of identifying dependencies within software system components in order to carry out meaningful impact analysis are highlighted in [88–90].

Change propagation. Change propagation refers to a phenomenon where a change to one part of the system creates a need for changes in other parts of the software system [90, 91]. Internal dependencies or relations between software components also play a vital role in evaluating the impact of software change. For example, a study of a Health Management System (HMS) by Sjøberg found relations between components of the system to have grown by 139% affecting all relations suggesting prior knowledge of interconnection between the system components might not be adequate to inform effecting changes [92].

Implement change. At this point, the change is applied to the system by implementing the change. Activities at this stage need be done with caution because processes at this stage can introduce bugs into the software and render it dysfunctional, requiring more time to fix.

Re-verify system. After translating identified changes to the software, it is critical to have the software system re-evaluated in order to ensure it meets its new requirements and continues to provide previous features that have not been removed.

The points outlined above are crucial software evolution activities which can come at very high costs to the developers because of the time, effort, and resources expended during analyses, implementation and re-verification. As previously discussed, often small changes to an artefact result in cyclic re-execution of these processes (i.e., change analysis, implementation, re-verification). At the same time it often results in redundant re-computations because changes don't always impact on the full system. Often, not every artefact modification may necessitate the re-construction of other development artefacts, hence, ideally, only affected artefacts or system components should be re-constructed.

In this section we have considered a broad view of software evolution and discussed factors that cause software to change. In addition, we discussed the costs associated with software evolution activities and outlined techniques that are commonly applied during software evolution. The next section will provide an expanded discussion of software evolution in the context of MDE with particular focus on model transformation.

2.5 Incremental Model Transformation

As discussed in the previous section, software evolution is an inevitable software engineering phenomenon because of a number of reasons (e.g., changing user requirements). In the context of MDE, since models are used to represent several aspects of a system, including user requirements, constraints, configuration, etc., whenever the underlying models of a system are modified, other dependent artefacts (e.g., system code, other models, etc.) need to be evolved accordingly. Synchronization of system artefacts is typically achieved through model transformations. For example, M2T transformation for textual artefacts and M2M transformation for other model-based artefacts.

As discussed in Section 2.3, the lack of support for scalable model management tasks such as efficient change propagation has hampered the adoption of MDE techniques in industry. In a model-based system (software that has been constructed using a model-driven approach), changes typically first manifest in the underlying model(s) of the system. In response to model modifications, other artefacts of the development require updates based on the model changes. The propagation of changes from one model to other artefacts is often achieved through model transformations. It can be manual (instantiated by the developer) or automatic.

There are two established strategies for propagating changes in model transformations: batch and incremental. Batch transformation entails re-executing a transformation in its entirety without consideration for what the changes are nor what the effect of the changes will be on other artefacts. In other words, the batch transformation strategy ignores the software evolution activities (i.e., change detection, impact analysis, change implementation) discussed in Section 2.4.1. There are obvious deficiencies in this strategy: it results in redundant re-computations, time and resource wasting [93, 94]. Model transformation which requires re-computing the whole transformation when only a small fraction of the source model changed do not scale very well [18]. Conversely, incremental change propagation strategies are typically based on narrowing the scope (change detection) of re-execution of a transformation to only the affected parts of the source models (impact analysis). In general, incrementality in software engineering refers to the process of reacting to changes in an artefact in a manner that minimises the

need for redundant re-computations. Turnaround time for small incremental changes are important metrics of concern for model transformations [9]. Hence, incremental model transformation has been the subject of much research.

Czarnecki [64] describes three types of incrementality: target, source, and user edit-preserving incrementality. These descriptions are based on the following properties of the model evolution: 1.) source of change (either source or target model), 2.) selective change propagation, 3.) data preservation.

Target incrementality refers to the process of updating a target artefact based on the changes made to a source model. It entails re-executing a transformation on the entirety of a source model which produces a new target model that is then merged with previous target model. Target incremental transformations are very similar to batch transformations in that the transformation is executed in its entirety, but differs by merging new content with pre-existing artefacts whereas batch transformation overwrites the pre-exiting artefacts. The transformation engine relies on trace link information to determine which element in the target requires updating and which elements in the source model requires transforming and creating in the target. Trace links contain historical data of previous transformations with which the transformation engine can map elements in a source to elements in the target [95]. Target incrementality does not take into consideration, the amount of source model elements that need to be examined.

Source incrementality improves on target incrementality by seeking to eliminate the need to perform a merge. It limits the execution of a transformation to only changed parts of source models. This ensures only affected artefacts of the transformation are re-constructed. As such, change detection and impact analysis are important steps performed by a source-incremental transformation algorithm. This can improve efficiency especially when the source models are large, complex (with associations between model elements). Furthermore, because the source incrementality limits the re-execution of transformations to affected parts of the transformation, it enables incremental transformations that scale by the magnitude of input model changes (or the impact of the changes) rather than by the size of the source model.

However, the effectiveness (extent to which the source incremental algorithm can reduce redundant re-computations) depends largely on the level of granularity (e.g file, model element, model element feature). For example, if the granularity or unit of change is an entire model, the transformation can be re-executed on that particular model (e.g., by comparing the timestamp of the model file to the time of the last execution of the transformation). However, change consideration at such a high level can result in an

overly pessimistic transformation. That is, the impact analysis is imprecise and thus, is less effective in reducing redundant re-computations.

User edit-preserving incrementality enables the preservation of manually crafted changes in generated artefacts. For example, in the context of M2T this is a desirable feature for transformation engines considering that not all transformations yield a fully working system and instead leaves gaps to be plugged by hand-written code. In practice, there is sometimes a need to edit generated text, make some change to the source model(s), and then run the transformation again. It is crucial that this chain of events does not result in loss of user-edited text.

In addition to these types of incrementality, there are two execution modes of an incremental algorithm which are based on the application of an incremental execution: offline and online (or live). In offline mode, an incremental algorithm is applied to a transformation on demand (*after the source model update*). In this mode, the transformation is re-executed only when re-synchronization of artefacts is required after model editing, for example, whenever a new version of the source model is available. On the other hand, in online mode, incremental re-executions of transformations are performed on-the-fly (*during the source model update*). In contrast to offline mode which requires a new version of a source model, in online mode changes are propagated as they occur in the source model. This characteristic is particularly useful in a development environment where changes are frequent and immediate feedback of the effects of the source model changes are important.

2.5.1 Incremental M2M Transformation

M2M transformation scenarios can comprise several source and target models which need to be synchronised. Typically, synchronising models involve applying updates from the source model to the target model. One approach is to re-run the entire transformation against the source model to produce a new target model which is then merged with the previous target model. Another approach is to compare the source model with a previous version after each change to in order to detect differences (or a delta model). The transformation is then executed against the *delta* producing a difference target model that is then merged with the previous target model producing a new target model.

A live updating approach is proposed in [96] which uses a tree to represent the trace of a transformation execution. Each node represents either a source or target element, and the edges are rules. The transformation context exists as a whole and is maintained throughout all transformation executions. Thus, as changes are made to the source

model, the changes reflect in the tree and the target is deduced from the tree. For example if an element is added to the source, the transformation searches for a matching rule and model element in the tree. If it finds one, it updates the node, otherwise, it spawns another edge and node in the tree. This way, the transformation eliminates the need of a merge algorithm for merging incremental targets. The advantage of this method is that the amount of computation required is proportional to the size of the input changes and the output changes [96]. The drawback however is that it maintains the transformation context for every execution. Considering that this grows as the source model grows, it can be an issue for large, complex transformations. Another possible drawback of this technique is that its efficiency depends on the tree search algorithm. Finally, when changes are made to transformation rules, it can render parts of the transformation context invalid because of rule mis-matches, for example, $r : a \rightarrow a'$ is changed to $r : a \rightarrow b'$

In [97], an incremental M2M transformation technique with Triple Graph Grammars (TGG) is presented. The algorithm exploits dependencies between transformation rules to achieve incrementality. It stores traceability information to maintain consistency between source and target models. Additionally, the correspondence model has a correspondence node with a self-association which connects each correspondence node to its predecessors. Thus, a rule in TGG specifies a correspondence mapping between the elements of the source and the target models. A graph grammar rule is applied by substituting the left hand side (LHS) with the right hand side (RHS) if the pattern on the LHS can be matched to a pattern in the correspondence model [97]. A directed edge from the correspondence node to the created target element is inserted each time a rule is successfully applied. This reflects the dependencies and execution order of the rules. So, by traversing the directed acyclic graph created by the correspondence nodes, inconsistencies between the source and target models can be determined, which is done by retrieving the rule which was used to create the correspondence node and checking if it still matches the current situation. If any inconsistency is detected due to a deletion in the source for example, it deletes the created target element and the correspondence node. This way, the algorithm achieves incrementality by not re-running the transformation against the entire source model but it incurs a cost in all correspondence nodes by comparing it with patterns in the source model. A potential drawback to this approach lies in the amount of space required to maintain an intermediate model which grows by every transformation execution because it stores the source-rule-target information.

A similar TGG-based incremental transformation technique is later proposed by Giese et. al [98]. This technique requires TGG rules to be deterministic and assumes only source model modification. In contrast to [97], it supports live change propagation.

To detect model element modifications, an event listener is attached to each model element in the source. Whenever an element is modified, its associated correspondence node is put in a transformation queue. Thereafter, the queue is processed by executing specific synchronization rules on the elements contained in the queue. Synchronization rules are responsible for maintaining consistency between associated source and target models by first checking the structure of the matching source and target elements before checking checking attribute equality.

A different incremental graph-based transformation technique called incremental pattern matching is presented Ráth et. al. [99]. Graph patterns are atomic units of model transformations which define constraints that nust be satisfied for model manipulation to take place. In case of incremental pattern matching, graph patterns are defined on model elements, and whenever the model is modified, graph patterns are updated. This approach is based on the RETE algorithm. RETE is an efficient algorithm for comparing large collections of patterns to collections of objects [100]. Transformation information is represented as tuples and nodes. Tuples contain model elements. Nodes refer to patterns and store tuples that conform to a pattern. When changes are applied to a model element, update signals are sent through outgoing edges, then each receiving node updates its stored tuples, and where applicable, more update signals are generated and propagated through the graph.

Bergmann et. al. [101] presents a fundamentally different approach which defines the concept of *change history models*. Change history models are essentially a log of elementary model changes derived from performing simple operations on model elements. Basically, the change history models are are trace models which contain sequences of model manipulation operations. So, whenever a change is applied to the model, the change history model is updated and associated rule is invoked. Since this technique focuses on bi-directional transformation (i.e., transformation in which target elements can also be translated to source elements), a change history model of the target model is also tracked. Incrementality is achieved by mapping the change history model of the source and target models based on a generic metamodel that captures model manipulation operations, e.g., *createElement, setAttribute*. A distinct feature of this technique is that transformation mapping takes place between model manipulation operations in the change history model of both source and target models rather than on the source and target models. The drawback of this technique is that because transformation can be executed in two directions, the order of model manipulation operations in change history logs must be preserved.

Jouault and Tisi [93] propose an incremental technique for ATL that is based on creating bindings of OCL expressions to model elements. The bindings represent dependency

information between specific rules and OCL expressions evaluated during the execution of the rules. With the dependency information, when changes are applied to the source model, exact rules which consume the modified model elements can be determined, and the rule re-executed on such elements. This technique is different to the ones described above in that it relies on tracking transformation execution information. However, it exhibits a crucial limitation. It does not track imperative statements. As such, model elements accessed within imperative blocks can not be monitored. This compromises the correctness of the transformations that are executed with this incremental engine.

Of the reviewed incremental M2M transformation techniques, three ([96–98]) are purely declarative in nature. As such they are not amenable to transformations that require complex operations. On the other hand, three of the techniques ([93, 99, 101]) combine declarative and imperative constructs. However, they do not support incremental execution of imperative parts, instead [101] and [99] re-execute all imperative parts, hence, they are overly pessimistic and limit the benefits of incrementality. On the other hand [93] completely ignores imperative parts, thus it compromises the correctness of the transformation.

2.5.2 Incremental M2T Transformation

The types of incrementality described in the previous section have differing characteristics. For example, target incrementality re-executes a transformation in its entirety while source incrementality limits transformation re-execution to a subset of the source model. User-edit preservation prevents loss of manually crafted contents. The primary objective of an incremental algorithm in the context of the requirements of scalable transformations (discussed in Section 2.3) is to reduce or eliminate redundant re-computations.

Based on the execution strategy of target incremental algorithms, they can only partially fulfil this objective. The efficiency of target incremental algorithms is largely dependent on the physical machine (e.g., read/write speeds of hard drives) on which the transformation is executed. This is because target incrementality prescribes that a transformation is wholly re-executed before the outputs of template re-executions are compared to previously generated artefacts to determine whether the newly generated contents should be written to disk. However, since the re-execution of the transformation has already taken place, by the time comparisons of the outputs of the re-executed templates are compared to the contents of pre-existing artefacts, potentially redundant re-computations have also been performed. Source incremental algorithms on the other hand can minimize redundant re-computations because they limit the re-execution of

transformations to changed parts of the source model. Hence, user edit preservation can be used in conjunction with source incrementality, because when hand-written text is added to generated artefacts, there is no need to run the transformation until changes are made to the source model.

2.5.2.1 Analysis of Incrementality in M2T Languages

As none of the reviewed literature analyses incrementality in M2T languages, this section discusses and evaluates three M2T languages' support for incrementality. The three languages chosen are T4[9], EGL, and Acceleo. EGL and Acceleo were chosen because they are open source, supported and actively used in research, moreover, EGL is developed at York, and Acceleo is an implementation of OMG's M2T standard [102]. T4 was chosen because its also freely available and popular among Visual Studio developers[10]. The languages were applied to an example of incremental transformation, which has been developed specifically for this analysis. The same example metamodel and source model were used for each change scenario, the behaviour of each language was observed. The result of the analysis is summarised in Table 2.1 and explained in the remainder of this section.

Table 2.1: Language Comparisons

Language	Source	Target	User edit preserving
Acceleo	✗	✓	✓
EGL	✗	✓	✓
T4	✗	✓	✗

Consider the model displayed in Figure 2.11 which conforms to the metamodel shown in Figure 2.1. The model consists of two instances each of Student and Module, and three instances of Grade. Initially, the template shown in Listing 2.5 is executed on the source model and it generates student transcripts shown in Figure 2.12. In subsequent iterations of this transformation, the source model is modified before re-executing the transformation.

In the first iteration, the chosen M2T languages' support for user-edit preservation is assessed. As such, the previously generated transcripts are edited by manually adding some text to the protected region. Afterwards, each Grade is modified by changing its marks, and the template is re-executed. Subsequently, in the second iteration, support for target incrementality is assessed. So, the IDs of both students (*s1 and s2*) are changed and a new student *s3* is created. A target incremental transformation

[9] http://msdn.microsoft.com/en-gb/library/vstudio/bb126445.aspx
[10] http://www.olegsych.com/2007/12/text-template-transformation-toolkit/

engine would regenerate both transcripts and an additional transcript for *s3*. Finally, to assess support for source incrementality we restricted the model modification to a single model element (*s1's address*) and wrote text to the generated transcripts (outside the protected regions). Given these types of changes, ideally a source-incremental transformation engine will not regenerate any of the transcripts because: 1.) the first change is model-based and the changed model element property is irrelevant to the transformation, and 2.) the second change is non-model based and is outside of a protected region, so the transformation engine should not be aware of this change.

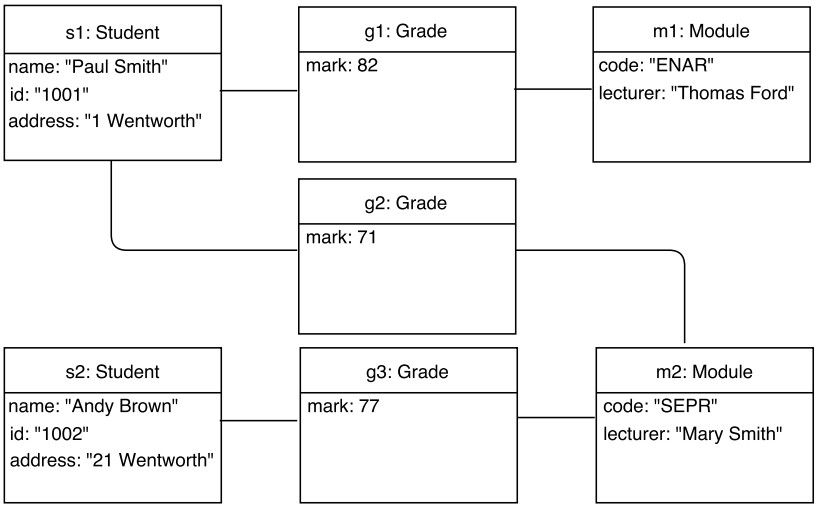


FIGURE 2.11: Example of University model that conforms to metamodel in Figure 2.1

```
1  [comment encoding = UTF-8 /]
2  [module student('university')]
3
4  [template public generateElement(aStudent : Student)]
5  [comment @main /]
6  [file (aStudent.name.concat('.txt'), false, 'UTF-8')]
7  Transcript
8  -------------
9  Student name:   [ aStudent.name /]
10 ID:         [ aStudent.id /]
11
12 Module    (Grades)
13 [for (g : Grade | aStudent.grades) separator('\n')]
14 [g.module.name /]  [g.mark /]
15 [/for]
16
17 Remarks:
18 [protected ('notes')]
19
20 [/protected]
21 [/file]
22 [/template]
```

LISTING 2.5: Text Generation from university model in Figure 2.11 specified in Acceleo

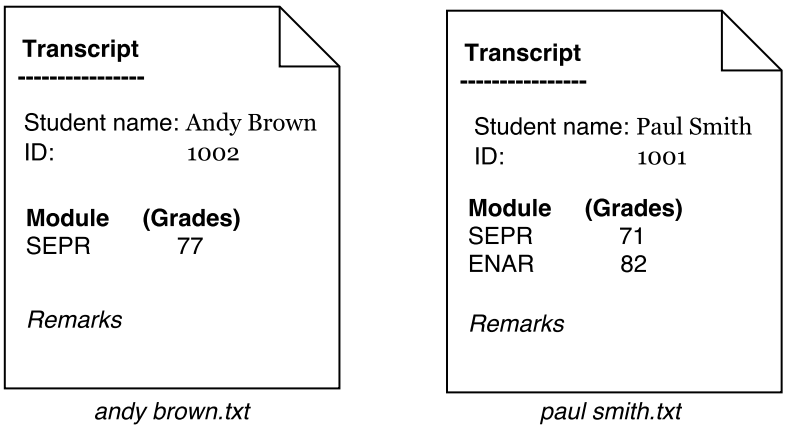


FIGURE 2.12: Text Generation from a Model

With respect to user-edit preservation, T4 does not support mixing generated text with hand-crafted text. EGL provides a special *startPreserve* tag with which it supports the preservation of user edits. This instructs the transformation engine to tag a protected region by appending a start marker for a protected region to the output buffer. The command takes two arguments: id (that uniquely identifies a protected region) and an enabled boolean parameter. The protected region is ended by an *endPreserve* command. Thus, any text manually written into the protected regions are preserved during subsequent transformations. Similarly, Acceleo (see Listing 2.5) preserves modifications of generated text by providing a 'protected' tag which provides the same functionality as the *startPreserve* tag in EGL.

In terms of target incrementality, all M2T languages under assessment support regeneration of text contents and overwriting the contents of previously generated files with the new content (if old and new contents differ). They also support the generation of new files when new model elements that are relevant to the transformation context are added to the source model.

With respect to source incrementality, T4, Acceleo and EGL do not provide support for source incrementality. After generating student transcripts (i.e., *paul smith.txt* from *s1*, *andy brown.txt* from *s2*, we modified the source model by changing the address of *s1*. Note that this change is an irrelevant change in the context of this transformation since the *Student2Transcript* template does not consume the address of a student. In order to compare the contents of the files without relying on only the files access attributes (*last accessed or modified time*), we added arbitrary text to the previously generated transcripts. After re-executing the transformation, both student transcripts were re-generated despite the fact that the change applied to the source model could

not have altered the contents of the generated transcripts. By adding arbitrary text to the generated transcript before re-executing the transformation, we could determine that the transformation engine always re-executed the templates before comparing their contents with the contents of previously generated files. Without the arbitrary text, simply inspecting the access properties of the generated files would not have revealed that the files were regenerated.

The above observations clearly indicate that T4, Acceleo and EGL exhibit the same characteristics with respect to target incrementality. Subsequent transformation results in writing data from all elements of the source model regardless of which model elements were modified required updating in the target, to an output buffer. Afterwards, the text of the buffer is compared to the contents of the output from previous transformation, and if the texts are not equal, the output buffer is written to disk to overwrite the existing target.

2.5.3 Discussion

With respect to incremental M2M transformation, most of the reviewed techniques first perform change detection by creating change history logs as source models are edited. Change history logs are beneficial in that they enable computation of changes without having to perform model differencing. Model differencing used for incremental transformation in tools such as QVTr [103] and Xpand (M2T) suffers from two main drawbacks. Firstly, model differencing requires at least two versions (old and new) of an input model, hence, it is memory intensive. Secondly, computing differences can be computationally more expensive than a batch re-execution because it requires at least two full model traversals. As such, the efficiency of transformation engines that use model differencing is largely dependent on the underlying modeling framework.

Although many incremental M2M languages use change history logs, and are not susceptible to the frailties of model differencing, the blanket application of incremental M2M techniques to M2T is not feasible because both types of transformations have different concerns, discussed in Section 2.2.3. Generally, M2M languages may be limited in their ability to handle unique features of M2T languages (e.g., handling protected regions, white spaces, escape direction, etc.). With respect to TGGs, as seen in the previous section, there has been considerable work on incrementality for triple-graph grammars – see [104] for a recent comparison – but TGGs are inherently declarative thus, they are generally not Turing-complete (although some do provide fallback mechanisms), whereas most M2T languages are Turing-complete, and hence, support complex model operations.

Furthermore, in M2T transformation languages rule execution scheduling is implicit whereas most M2M transformation languages (e.g., ETL, ATL, BOTL [105], etc.) allow explicit rule scheduling. Explicit rule scheduling has dedicated constructs to explicitly control the execution order of transformation rules. For example, in ATL and ETL, a transformation rule can be invoked directly inside another rule by annotating it as *lazy*. Such explicit declaration of rule scheduling thus presents an additional layer of processing for incremental M2M transformation languages. Specifically, in addition to change detection and impact analysis, rule dependency analysis also require careful consideration. However, considering that M2M transformations can be endogenous, handling rule dependency in the context of incrementality is not straightforward. As discussed in Section 2.5.1, of the reviewed incremental M2M transformation languages that have imperative features (i.e., [101], [99], [93]), none supports incremental execution of imperative parts of a transformation because of transformation rule dependency. Given that rule scheduling in M2T transformation engines is implicit, template execution paths are usually deterministic, hence may require a different approach.

Despite the above discussion, it is conceivable that M2T transformations can be implemented as sets of M2M transformations with an additional unparsing step that translates the output of such M2M transformations to the appropriate textual syntax of the target language. For example, generating Java code from a UML class diagram using such an approach will proceed in the following steps: a model that conforms to the metamodel of the target language (e.g., JaMoPP[11] metamodel in the case of Java code) is produced from the input UML model; and an unparser translates the generated target model to Java's textual syntax. The implementation of such a strategy would entail defining a metamodel, a parser (to support encoding static parts of the output of the transformation using the typically, more concise concrete syntax of the target language), static analysers (to resolve references), and an unparser for the target language. All of these steps present additional significant overheads to the transformation development process. Since unlike the case with Java, a metamodel of the target language may not already exist. Additionally, static analysers and unparsers for complex target languages do not already exist for major modeling platforms (e.g., Eclipse/EMF).

In addition to the above, from a practical standpoint, expressing M2T transformations as M2M transformations would require re-engineering M2M languages to accommodate common M2T features such as protected regions ([102]), which is far from straightforward.

Finally, because M2M languages are predominantly declarative in nature, current incremental M2M techniques only focus on the support of incremental execution of only

[11] http://www.jamopp.org/index.php/JaMoPP

declarative language parts [106]. In contrast, most M2T transformation languages are hybrid, and support complex calculations through imperative constructs. Hence, effective incremental techniques in M2T cannot ignore imperative parts of a transformation.

2.6 Incrementality in other areas of Software Engineering

The next sections of this report will discuss other areas where active work have been done in order to address challenges brought about by incremental change.

2.6.1 Incremental Compilation

A typical software project often contains several source code files with some dependencies among the source code files. Often changes to such software might involve any number of these source files. The number of changed source files, however does not determine the extent of the effect of such changes. Typically, the developer would have to re-compile the entire source files even for changes where re-compiling only the changed and related source files would suffice, resulting in a waste of development time. The cost of making a minor change to a large system may be so significant that it inhibits the growth and evolution of the system [107].

The answer to this problem was to devise a mechanism that will allow source files to be compiled incrementally. A simple approach is to determine the minimal separately compilable unit and recompile the smallest such unit after a change [108]. For line-oriented languages such as BASIC, it means recompiling a single statement, for Pascal recompiling a procedure [108]. However, for more complex languages like C++ or Java, it could mean recompiling several files. An example of a mechanism for incremental compilation is the make utility. The programmer defines dependencies between source files in a makefile allowing the compiler to construct a directed acyclic graph (DAG) of dependencies [109], and based on timestamp analysis of the source files, the compiler re-compiles the changed files and their dependent files. However, this mechanism suffers two shortcomings [109]:

1. The dependencies are specified manually and hence the specification is prone to error.

2. The comparisons of timestamps ignores specific change types. For example, declaring a new function in a C++ header file may not necessarily affect all dependent source files if only one of the source files will make use of this new function, yet all the related source files will be recompiled.

An incremental compilation algorithm for Java programs which has two core data structures is propesed in [109]: a SourceDependency which stores dependency information between source code files and a *ClassDatebase* that contains all class files generated by the compiler including the last compilation time. At first run of the compilation, the compiler creates a *SourceSet* (set of source files) and a *ClassSet* (set of class files). On subsequent compilations, all source files with newer timestamps than the stored last finishing time are added to a *DeltaSourceSet*. By comparing the *ClassDatebase* with the *SourceSet*, a *DeletedSourceSet*, *AddedSourceSet* and *ChangedSourceSet* are also derived. While the corresponding class files of files in the *DeletedSourceSet* are deleted, all source files in the *AddedSourceSet* and *ChangedSourceSet* are added to queue of source files to be compiled or re-compiled. Afterwards, for every source file in the queue, the compiler compares a newly generated class file with its pre-existing class file in the *ClassSet*. If the difference is not null, the newly generated class file of the source file overwrites its pre-existing class file in the *ClassSet* and updates the *SourceDependency* and *ClassDatebase*. The compiler also retrieves the dependent files of the source file and adds them to the queue.

A similar recompilation algorithm, the Smart recompilation [107] works almost exactly as the incremental compilation for Java programs [109] in that it also relies on conducting a change analysis to determine the impact of a change. It however differs in a few ways, the first of which is that it does not rely on timestamps for change analysis and secondly, its granularity reaches to declarations in the source files. The first time a source file is compiled, it creates and maintains a history log of all declarations in the source file along with a reference list of other declarations in other source files that it depends on. If a change is made to any source file, it checks for new declarations in the file not in the history log, creating an add set of declarations. It also creates a deleted set (*DeleteSet*) of declarations which contains declarations in the log, no longer in the source file and it creates a modified declarations set that contains declarations in the source file which is different to the same declaration in the log. Finally it determines which source files to recompile by checking if any declaration in its set of references and declarations are also in any one of the derived added, deleted and modified sets.

Magpie is an integrated interactive programming environment for Pascal which uses an incremental compilation technique [110]. For static analysis, Magpie's unit of incrementality is a single character within a fragment. A fragment corresponds to either a statement body, variable declaration, constant definition, function definition of a Pascal program. During static analysis, each fragment of the text is completely tokenised with special token markers to indicate unscanned portion of text or incomplete tokens. Tokens are leafs of the parse trees which can also be non-terminals or terminals with no associated token. Since any single editing change is bounded to a single fragment,

rather than the entire program, the resulting parse is incremental as it is limited to that fragment. This can potentially lead to a drastically reduced recompilation time, especially for large programs, because it limits recompilation to only the changed bits of a program file. However, like the Smart recompilation algorithm [107], due to the low level of granularity, it could also lead to an increased recompilation time because the lower the level of granularity, the higher the number of elements that have to be analysed to find changes. Although, smaller granularities provide more accurate information, they may be too detailed and voluminous [111]. For example, if the granularity was at the file level, the analysis will be to the order of the number of files, granularity levels below this can drastically increase this number. Thus, there can be situations where re-computation cost of an entire program file may be more efficient than the incremental approach. Additionally, due to the very low level of granularity, Magpie consumes a lot more storage space for the internal representation of the Pascal program [110].

2.6.2 Incremental Evaluation of OCL Constraints

MDE processes such as text generation and transformation involve querying models and performing well-formedness validation on the source models. Query evaluation entails a matching process where searches are conducted for model elements that satisfy the constraints defined in the query. An example of this is demonstrated by the guard block of an EGX transformation rule (See listing 2.3). Performing these related operations (querying and validation) on large models frequently can cause transformation execution time to become significantly high[96].

Incremental pattern matching (INC) is one approach to reducing the execution time of queries on large models [19]. INC stores the results of queries in a cache which are incrementally updated as changes are made to the source models. As a result, query results are fetched quicker than searching the source models again. EMF-IncQUERY [112] achieves the same goal by providing an interface for each declared pattern retrieving all matches of a pattern or by retrieving only a restricted set of matches. Like INC, queried patterns are cached and updated as changes are applied to the source models. The difference is that patterns are defined in the source model. A graph pattern represents constraints that have to be fulfilled by a subset of the instance model[112].

In a related effort, [113], propose an incremental integrity check algorithm which seeks to consider as few entities as possible when assessing integrity check violations. Integrity checking is the process of checking if then execution of an operation would violate any given integrity constarint. For example, an integrity constraint for the Student concept

in Figure 2.11 might enforce that no student is registered on more than four courses per term. [113]'s algorithm defines a new integrity check by choosing an entity that most likely will be affected by a change event such as adding a new module to a student's list of modules, then it computes the instances of this entity (Student) that may have been affected by this change event and finally an incremental expression is defined by refining the body of the original integrity check to be applied over only the relevant instances of the entity.

2.6.3 Incremental Updating of Relational Databases

Database mining is another area of research where the concept of incrementality appears to have received some attention because discovering association rules in large databases plays an important role in data mining activities. Thus, defining efficient incremental algorithms to update and manage association rules are equally important. Association rules refer to patterns identified in a data set, or if/then statements that help identify relationships between data that appear to be unrelated in a relational database. Database updates may introduce new association rules which may invalidate existing ones [114]. So, after a period of updating a database, new association rules need to be identified by scanning through the entire database.

The naive approach is to run the association rule mining algorithm on the entire updated database. Since the efficacy of an incremental algorithm lies in reducing the number of data sets to be considered, [114] propose a Fast update (FUP) algorithm which works by first determining the difference database (db), followed by scanning the db to find data sets with a support value larger than a predefined threshold value. For a data set X, its support value is defined as the percentage of transactions in the database which contain X.

Incremental re-computation of relational expressions is a relevant area of relational database management research. In the event of database updates, some derived data, integrity constraints and materialized views may become invalid resulting in a need to recompute queries. However, recomputing all queries and relational expressions can be very costly and could result in failure to meet performance requirements [115]. Qian [115] proposes an algorithm for incremental re-computation of relational expressions. Whenever an update takes place, an incremental set of relational expressions is derived by finding the difference set between previous relational expressions set and the new set (as a result of the update). For example, consider a database with a 'department' relation and another relation (a view) which contains departments whose employee salaries are greater than the department's budget. So, when an employee is

added to the department relation, rather than run the view queries, the added employee salary is simply added to the view. A potential problem with this approach however is that the difference set of a relation has to be computed, which can be time consuming, and in some instances an update may have no effect on other relations.

2.6.4 Discussion

As shown in the previous section, incrementality is common research theme in several areas of software engineering including maintenance of materialized database views, compiler technology, etc. Many of the reviewed incremental approaches have also exhibited similar characteristics; they are based on methods for computing deltas over considered artefacts. However, they differ in how the deltas are computed. For example, Liang uses timestamps of compiled Java classes to determine whether a source file has been modified. Cheung [114] computes stateful (compares two versions of an artefact) deltas from databases to detect changes. Other incremental approaches ([113, 115]) create change history logs as artefacts are being edited. The change history logs provide two benefits: the logged changes can be analysed and propagated live (on-the-fly) or they can be applied on-demand whenever the developer requires re-execution of a task. Live re-execution of tasks allow immediate feedback and synchronization of artefacts, however, it often requires the optimization of the change logs. For example, removing logs relating to update of an object that is subsequently deleted.

2.7 Summary

This chapter presented the fundamental concepts regarding the use of MDE practices in software development activities, and highlighted the potential benefits (e.g., increased productivity, improved efficiency, etc.) of MDE. In addition, this chapter reviewed software evolution and discussed common factors that necessitate the evolution of software, and the pattern of activities that have been observed to be commonly used to manage the evolution of software.

Furthermore, this chapter provided a detailed review of the maintenance challenges posed by changing artefacts of model-based software development, and how incremental model transformation can be used to propagate changes from input models to other dependent artefacts.

From the reviewed literature, we identified a major research problem: the lack of support for scalable model transformations in M2T. This presents a potential stumbling

block to efficient change propagation. Although there has been substantial research effort at addressing scalability issues in M2M transformation through source-incremental techniques, most M2T transformation languages do not support source-incrementality. Also, from the reviewed literature, there is no evidence suggesting that the existing source-incremental techniques in M2M are amenable to M2T languages. However, we provided arguments that because M2T and M2M transformations address different concerns, incremental M2M techniques may not be amenable to M2T languages.

In the next chapter, we will analyse the research challenges posed by incrementality in M2T transformation and demonstrate through an example M2T transformation how source-incrementality can be used to achieve efficient change propagation.

Chapter 3

Analysis and Hypothesis

Chapter 2 presented a detailed review of incremental model transformations. The review of the literature revealed that significantly more research has been conducted on incremental M2M transformation than incremental M2T transformation. In the review different forms and approaches to incremental model transformation were discussed and open challenges requiring further research were identified. Section 3.1 of this chapter summarizes these challenges. Section 3.2 discusses incremental transformation phases and techniques that can be applied at each phase.

3.1 Problem Analysis

The primary benefits of MDE include improved software quality and short turnaround time. However, the validity of this assertion is threatened by the lack of tools that support model management tasks (e.g., model transformation) that scale. During a software development life cycle, the evolution of input models often necessitates the re-synchronisation of generated artefacts with the evolved input models. Re-synchronisation of dependent artefacts with evolved input models is often achieved through the re-execution of a transformation in its *entirety* (batch transformation). Batch transformation often results in a wasteful change propagation process because resources are expended on the re-execution of potentially *redundant computations*, particularly when only a small portion of the input model is changed.

Since a batch transformation engine propagates changes by re-executing a transformation in its entirety, the re-execution time required by such a transformation engine is directly proportional to the size of the input models. In the worst case scenario, whenever irrelevant changes (changes which do not alter the output of a transformation) are applied to an input model, the transformation engine still requires the same

amount of time to re-execute the transformation as it did during the first execution. As stated in [18, 26], model transformations which require complete re-execution when only a small fraction of the source model changes, do not scale very well. Since batch transformation re-executions scale linearly with the size of the input model, as the size of the input model increases (e.g., adding twice as many model elements), the transformation engine performs a full traversal and query of the input model. Many of such model queries can be potentially unnecessary if the metamodel types of the added elements are not relevant to the transformation specification (i.e., none of the transformation rules apply to the metamodel type of the elements). In the worst case scenario, if all the model changes are relevant, the time required to re-execute such a transformation increases by the proportion of change to the input model size. As such, the re-execution time and space requirements of a batch transformation scales by the size of the input model. Accordingly, we define a scalable transformation as one in which the re-execution time and space utilization following the re-generation of artefacts (after the input model is modified) are proportional to the impact of the input model changes. Arguably, reducing or eliminating the amount of redundant computation that takes place during transformation re-executions can improve the efficiency of propagating changes from input models to dependent artefacts.

Furthermore, in M2T transformation, naively re-executing a transformation in batch mode typically fails to remove obsolete files generated in previous transformation invocations. A batch transformation engine cannot remove obsolete generated files from transformation output directories because the transformation re-execution does not care about detecting specific changes that have been applied to the input models. On the other hand, a source-incremental transformation engine can detect and remove obsolete generated files by re-executing the transformation on only changed parts of the input model. The ability of a transformation engine to re-execute a transformation on only the changed parts of an input model is therefore, crucial.

Despite the prevalent use of M2T transformation in MDE, most contemporary M2T languages do not possess the capability to re-generate textual artefacts based on only the changes that have been applied to source models. As discussed in Section 2.5, only source-incrementality enables a transformation engine to perform such selective transformation in order to reduce redundant re-computations.

In light of the above, this thesis explores the following hypothesis:

- *Contemporary M2T transformation languages can be extended with novel and practicable techniques which enable correct and efficient source-incremental transformations without sacrificing the expressiveness of the M2T language.*

- *There exists a threshold of the proportion of model changes at which source-incremental execution ceases to be more efficient than non-incremental execution of a M2T transformation.*

Many model management tasks are actualised through tools which are results of several years of research [23]. MDE tools (e.g., Epsilon, ATL, VIATRA) enable the automation of model management tasks and orchestration of tasks in heterogeneous development environments. Therefore, given the importance of tools in model management processes, the compatibility of the proposed source-incremental techniques with existing M2T languages is important. This prevents re-inventing the wheel since most existing M2T tools are products of rigorous research. In addition to this, backwards compatibility will allow pre-existing implementations of M2T transformations to benefit from source-incremental executions, and also maintain the expressiveness of the M2T languages.

Practicable source-incremental techniques should allow the transformation engine to support black box executions of transformations. That is, the incremental execution of transformations should be transparent to the transformation developer, and ideally not require extensive amounts of human intervention. In addition to this, source-incremental transformation techniques should not impose unreasonable costs on the transformation engine. For example, the RAM space cost incurred by the transformation engine should not exceed amounts of space typically available on modern machines.

Additionally, the output produced by applying source-incremental techniques to the execution of a M2T transformation should be indistinguishable from the output produced by executing the same M2T transformation using a batch transformation technique on a clean output directory.

Furthermore, efficient source-incremental transformation techniques should require less time to execute compared to a batch execution of an equivalent M2T transformation. However, considering that source-incremental transformation engines expend time initially on change detection, impact analysis, and change propagation, it is conceivable that for high-impact changes (i.e., changes that require a large proportion of templates to be re-executed), a batch re-execution of a transformation can require less time compared to a source-incremental execution.

In light of the shortcomings of a batch transformation engine, and transformation engines that only support target incrementality[1], efficient incremental transformation

[1]Target incrementality does not address the fundamental scalability challenge: transformations re-executions do not scale with respect to the size of the change of the input model.

can arguably only be achieved through source-incrementality alone, when the preservation of user-crafted text is not taken into consideration, and a combination of source-incrementality and user-edit preservation when preservation of user-crafted text is important. Hence, the main criteria for assessing the effectiveness of an incremental transformation engine are:

Correctness: The output of an incremental execution of a M2T transformation must be correct, i.e., the output must contain the same generated artefacts (excluding obsolete ones) as the generated artefacts of a batch execution of the same transformation. In addition, the contents of the files must be the same as the contents of a corresponding file produced by a non-incremental execution of the same transformation.

Source-minimality: The re-execution of a transformation should be constrained to only parts of the input model that are affected by the change(s). The main characteristic of source-incrementality is that it is a selective re-execution of only rule invocations that are relevant to the changes that are applied to an evolved model.

Time-efficiency: The processes of detecting changes, impact analysis, change propagation which constitute the steps of a source-incremental technique must be comparatively more efficient than a non-incremental execution. In other words, the execution of the additional steps that enables source-incrementality must not take longer than a non-incremental transformation engine would require to re-execute the same transformation.

Target-minimality: Target-minimality describes the ability of a transformation engine to maintain a clean transformation output directory by removing any previously generated artefact that has become obsolete due to input model changes, e.g., the deletion of a model element. The transformation engine must be able to detect polluting generated artefacts of the transformation. This can be important in particular for transformations that generate application code. For example, obsolete source files can result in uncompilable application code.

Based on the research hypothesis and the criteria for effective incremental transformation engines outlined above, we will investigate the following questions:

Q1: Can source-incremental M2T transformations produce outputs that are indistinguishable from the outputs of equivalent non-incremental M2T transformations?

Q2: To what extent does source-incrementality enable M2T transformation engines to reduce the amount of redundant re-computations which are performed by non-incremental engines?

Q3: Can source-incrementality guarantee the removal of previously generated obsolete artefacts? As discussed later in Section 6.1.1.3, maintaining clean transformation output directories can be an important consideration for M2T transformations, e.g., for M2T testing, code generation.

Q4: Under what circumstances are source-incremental executions of M2T transformations more time-efficient (i.e., are faster) than non-incremental M2T transformation engines?

Q5: How much more memory and disk space cost does the source-incremental execution of M2T transformations incur compared to non-incremental M2T transformations?

Q6: How is the performance of a source-incremental M2T engine affected by increasing the magnitude of input model changes?

Q7: How is the performance of a source-incremental M2T engine affected by increasing input model sizes?

3.2 Incremental Transformation Phases and Techniques

We anticipate that source incrementality in M2T can be achieved by designing algorithms that are based on the software evolution techniques discussed in Section 2.4. Thus, the main steps of a source-incremental transformation algorithm can be decomposed into three phases which are executed in sequence: change detection, impact analysis, and change propagation.

3.2.1 Change Detection

Change detection is the process whereby the transformation engine first seeks to identify model elements that have been modified since the last successful execution of a transformation. Typically, when an input model is modified, it entails the application of three types of change operations: addition, deletion, and modification of model elements. Addition operations occur when a new model element has been created in the input model. Deletion operations occur when a model element is deleted from an input model. Modification operations refer to any kind of change that alters the state of a pre-existing model element. For example, setting the value of a model element's feature. Modification operations could also be as a result of the addition of a model element (new or pre-existing) to a list-based feature of another model element, or as a result of the deletion of a model element which refers to another model element.

Change detection can be achieved in the following ways: using model differencing algorithms, and change history logs (that are created during model editing). Incremental transformation techniques such as Xpand2 (for M2T) favour model differencing for detecting changes while many M2M approaches, employ change history logs [93, 98, 99, 116].

Model Differencing. In a model differencing approach, the original and evolved models are compared to obtain a difference model. A difference model comprises model elements from the evolved model element that contain modifications, with respect to the original model. Once the model difference is obtained, an incremental transformation engine re-executes the transformation on the difference model instead of the entire evolved model. The effectiveness of model differencing techniques is largely dependent on the ability of the underlying modelling framework to compute difference models in an efficient manner. In contrast to change recording, model differencing is performed before the execution of the transformation, and it does not depend on receiving notifications about changes from an underlying modelling framework. However, despite its popularity, its effectiveness can be limited by two factors: memory overhead and computationally expensive model traversals. Firstly, in order to compute a difference model, at least two versions of the model need to be loaded into memory. While this requirement might be a reasonable compromise for achieving incrementality, it requires that an older version of the model is always available, which might not be guaranteed. Secondly, model differencing requires two model traversals. It is conceivable that the amount of time required to compute difference models will be directly proportional to the sizes of the models. Therefore, even for small changes on large models, computing difference models might become computationally expensive to the point that re-executing a transformation in non-incremental mode might execute faster.

Operation-based Change Recording. Operation based change recording algorithms are based on recording model element access operations performed during transformation execution. Recording model element property accesses at runtime ensures that only relevant parts (accessed model element properties) of a model are monitored and considered for change propagation. Before the re-execution of a transformation, model changes can be computed by querying the model to determine which recorded model element access operations evaluate to different values. Unlike model differencing, only one version of the input model is required to compute model differences. Another advantage of this approach over model differencing is that it can applied in an online (or live) transformation context.

In an online context, model evolution is monitored by a tool. The transformation engine depends on the tool to provide notifications of changes as they occur in the model. Change notifications are sent to the transformation engine as they occur, and based on the transformation configuration, the transformation engine might immediately re-execute the transformation or queue the change notifications for processing at a later time. Change recording affords the transformation engine the ability to perform live (immediate) re-execution of transformation. A challenge with change recording is that it enforces a dependency of the transformation engine on the underlying modelling framework to provide change notifications. Furthermore, the change notification tool cannot determine which changes are relevant to a transformation and which are not, hence, the transformation engine can be inundated with irrelevant change notifications which it will have to filter out.

Change History Logs. Change history logs are computed from modification operations on model elements. A change history log is derived from a sequence of change operations performed on model elements. It contains relevant information such as model elements and the model element properties that are modified. With such data, affected model elements can be determined without the need to perform model differencing. Furthermore, unlike model differencing, only one version of an input model is required. However, this approach can be limited by its reliance on the underlying modelling framework to monitor change operations on input model elements. Another potential drawback of this approach is that the change log can contain irrelevant changes (i.e., changes that are irrelevant to the transformation context), and may require additional processing to optimize (For example, removing duplicate change log items).

Timestamps. Timestamp based algorithms can be used to detect changes in software artefacts. Liang [109] presents an example of the use of timestamp analysis strategy for incremental compilation of Java programs. Another example is the make utility used in C/C++ projects, where the compiler selects source files that need to be re-compiled based on the timestamps of the source files and the make file. This kind of mechanism allows the identification of changed artefacts in software projects. This approach can be used for model transformations as well - selective re-transformation can be performed against model elements whose timestamps are newer than that of the templates that use them. However, it is impractical because current modelling frameworks do not commonly support timestamps at that level of granularity (i.e., model elements).

3.2.2 Impact Analysis

Impact analysis is another important process that is carried out by a source-incremental transformation engine. Through impact analysis, the transformation engine determines which transformation rule invocation will result in the generation of different contents compared to the output of the same rule invocation during a previous transformation execution. In [70], Kolovos observes that source incrementality is difficult especially when the transformation involves complex calculations. Complex transformations may introduce additional variables while generating text and often invoke complex queries on models, creating numerous paths in both model traversing and text generation. Such complex calculations make it difficult to define and maintain links between model elements and generated artefacts. This can make it especially difficult to propagate changes to generated artefacts accurately. Additionally, since it is possible to manually edit generated artefacts, preserving manual editions on subsequent re-transformations would require effort identifying, for example, precise location of the edits, updating dynamic sections only.

In addition to challenges posed by complex operations, in order to perform a precise impact analysis, transformation templates must be closed and not contain non-deterministic constructs. A closed template takes its data only from input models, which means that the generated text is dependent only on input model data. An example of a template that is not closed is shown in Listing 3.1. The template contains code that accesses data from a database resource (line 7), and in this case the data returned from the resource is beyond direct monitoring by the transformation engine. A deterministic template is one in which we can always predict which parts of the input models the template will access. Non-determinism may be introduced into a template (for example Listing 3.2) through the use of programming language constructs that can cause the template to generate random contents or cause the execution flow of a template to proceed in unpredictable paths. For example, the use of random number generators and access to a genuinely unordered features collection, Java collections (e.g., HashMap) whose access order is unpredictable.

```
1 Course Report for [%= aCourse.name %]
2 Lecturer: [%= aCourse.lecturer %]
3
4 Number of students:[%= aCourse.grades.size() %]
5 Average mark:[%=aCourse.grades.collect(mark).sum()/aCourse.grades.size() %]
6
7 This report was generated from [%= readDataFromDatabase %]
```

LISTING 3.1: Example of a non-stateless M2T template specified in EGL syntax

```
1  Course Report for [%= aCourse.name %]
2  Lecturer: [%= aCourse.lecturer %]
3
4  [% var student = aCourse.grades.random().student;
5  if(student.isHomeStudent()) {
6  ...
7  }
8  else {
9  ...
10 }
11 %]
```

LISTING 3.2: Example of a non-deterministic M2T template specified in EGL syntax

Static Analysis. Static analysis is commonly applied to detect syntax errors and perform optimizations at program design time. During static analysis the structure of the program is analysed without executing the program. The information assessed by a static analyser, for example, includes variable initializations and usages of the variables. Given the program traversal path knowledge obtained from static analysis, applying static analysis to M2T templates is plausible since information such as model element property accesses can be pre-determined by a static analyser before executing a template. However, as discussed by Fairley, there are theoretical and practical limitations to static analysis [117]. A primary theoretical limitation is that it is impossible to determine a complete set of possible program execution paths for an arbitrary program, written in a Turing-complete language, and executed on arbitrary input data. According to decidability theory [118], in the general case it is impossible to algorithmically examine an arbitrary program and determine whether it will execute a particular statement.

On a practical note, contemporary M2T languages are normally dynamically-typed and support features, such as dynamic dispatch that inhibit precise static analysis. For instance, static analysis cannot fully determine all possible execution paths nor usage of variables in templates that contain unknown types (either variables or functions). In addition, in languages that support random generators, it is impossible to always accurately pre-determine the execution path of the program before runtime. For example, consider the template in Listing 3.3, line 1 selects a random person, and the execution branches into the *if* statement or the *else* block depending on some properties of a *randomly* selected person.

3.2.3 Change Propagation

Change propagation takes place once the transformation engine has been able to identify relevant model element changes and determine which files need to be re-generated.

```
1 var person = persons.random();
2 [% if(person.followers.size() > 100) { %]
3   ...
4 [% else { %]
5   ...
6   [% } %]
7 [% } %]
```

LISTING 3.3: Example of a EGL template with unpredictable execution path.

Change propagation strategies are not discussed in the literature possibly because it seems to be a straightforward process, considering that it is the last step after change detection and impact analysis. However, change propagation poses a difficult challenge of its own.

Since M2T transformations are parametrized, i.e., a template invocation is a function that takes a template, a set of model elements, and other variables as arguments (see MOFM2T example in Listing 2.2); as the set of model elements passed to a template invocation are determined at runtime, change detection and impact analysis are not adequate to ensure efficient re-synchronisation of generated artefacts with input models. Careful consideration has to be put into how template invocations are re-executed based on the outcome of change detection and impact analysis. Ideally, the transformation engine should also possess the capability to map the re-execution of affected template invocations to specific model elements.

Co-ordination mechanism. In order to address the challenge discussed above, a co-ordination mechanism that orchestrates rule invocation executions and explicitly maps a single instance of a template invocation to a model element is conceivable. Such a co-ordination mechanism as implemented in EGL is discussed in Section 2.2.2.4. It enables the establishment of a traceable link between a template invocation and specific model elements. Hence, the results (i.e., model elements and template invocations) of change detection can be re-executed independent of non-affected parts of the transformation.

3.2.4 Discussion

To the best of our knowledge, Xpand[2] is the only contemporary M2T language that supports source incremental transformation. Incremental generation in Xpand uses a combination of trace links and model differencing techniques. Difference models are used to determine the changed subset of input models, and trace links are used to specify how source model elements are mapped to generated files. Once the difference model is constructed, impact analysis is performed to determine which changed model

[2] http://eclipse.org/modeling/m2t/?project=xpand

elements are used in which templates. A template is re-executed if it consumes a model element that has changed. The efficiency of the approach to incrementality employed by Xpand is heavily dependent on the effectiveness of the underlying modelling framework in performing model differencing. In Chapter 6 which is dedicated to evaluation of the proposed source-incremental techniques in this thesis, we compare (with respect to transformation execution time) the source-incremental techniques proposed in this thesis with the incremental technique of Xpand.

As discussed in Section 3.2, typical incremental transformation execution is performed in three dependent phases in the following order: change detection, impact analysis, and change propagation. From the reviewed literature in Chapter 2, many incremental transformation techniques (mainly M2M transformations) employ operation-based monitoring of model evolution through which they create change history logs over models. In many cases the change history logs are sufficient for determining what changes have been applied to input models. In response to model changes, impact analysis entails analysing the change history logs to determine which transformation rules invocations require re-execution. Finally, change propagation is performed by re-executing relevant parts of the transformation, and applying updates to the target models. This approach follows a sequential execution of three steps in which impact analysis is dependent on change detection, and change propagation on impact analysis. A potential drawback of this approach is that change detection can be imprecise and detect changes that are irrelevant to the transformation. Hence, impact analysis can potentially be a long-running process which diminishes the runtime efficiency of the transformation engine.

3.3 Summary

This chapter provided detailed discussions on the research challenges related to the inability of M2T tools to achieve scalable transformations by supporting incrementality. It also established the hypothesis and objectives of the thesis. The following chapters will discuss the designs and implementations of the source-incremental techniques proposed in this thesis, and will evaluate these techniques against the proposed hypothesis.

Through a review of literature we identified scalability as a challenge in MDE, and investigated this challenge in the context of M2T transformations. We explored the current state of support for incrementality in M2T by analysing contemporary M2T languages (i.e., Acceleo, EGL, T4), and identified the lack of support for source-incrementality by M2T transformation tools as a major contributing factor to their inability to achieve

scalable transformations. We also provided M2T specific definitions for the types of incremental model transformations. Our investigations led to the development of two different techniques, Signatures (Chapter 4) and Property access traces (Chapter 5) for enabling source incremental M2T transformations.

Chapter 4

Signatures

In the previous chapter, through analysis we established that an important criterion for an incremental transformation engine is that it provides source minimality, i.e., the ability to re-execute only template invocations whose output is likely to differ from the output that was obtained from a previous execution, based on the changes applied to an input model. This chapter presents one of the novel approaches to source-incrementality developed in this thesis - *Signatures*. Signatures are concise and lightweight proxies for templates that indicate whether or not a change to an input model can alter the output of a template. Instead of re-evaluating a template, the transformation engine undertakes a less computationally expensive operation of evaluating template signatures. The work on Signatures was published in [119, 120].

Section 4.1 provides an overview of the Signatures technique. Section 4.2 describes the key concepts that make up the Signatures. Section 4.3 discusses the two signature generation algorithms termed *Automatic* and *User-defined* signatures. Section 4.4 presents the implementation of the signatures technique in an existing M2T language (EGL). Section 4.5 compares automatic and user-defined signatures. Lastly, Section 4.6 concludes by summarizing the practicability, and the limitations of the Signatures technique.

4.1 Overview

Signatures are concise and lightweight proxies for templates that indicate whether or not a change to an input model will alter the output of a template. Signatures are computed during runtime, and contain subsets of the output obtained from the output of template invocations. Each signature value is a representation of the output of the invocation

of a template on a specific model element which can be used to determine whether the output of re-executing a template invocation will produce a different output, without re-executing all parts of the template.

The Signatures technique entails a two step approach to incremental model transformation. Change detection and impact analysis are combined into a single process (first step). In the second step, the transformation engine re-generates and/or creates files based on the outcome of the first step. The transformation engine using the signatures technique detects changes by re-computing and evaluating signatures, a process that entails querying only model elements that are relevant to the transformation, i.e., the transformation engine only checks for changes to the properties of model elements that are consumed by the transformation.

Since signature values are representative of the outputs of template invocations whose outputs are partly derived from model elements, they are sensitive to model element changes that may necessitate re-execution of the template invocations. So, instead of re-evaluating a template in its entirety, the transformation engine undertakes a less computationally expensive operation of evaluating template signatures. When a transformation is first executed, signatures are calculated and written to non-volatile storage. When a transformation is re-executed in response to changes to the source model, the signatures are recomputed and compared to those from the previous execution. A template invocation is re-executed only if its current signature differs from its previous signature. The efficiency of the signatures technique in providing source-incrementality is premised on the assumption that recomputing signatures, which only requires executing a subset of a template is less computationally expensive than re-executing a template in its entirety.

4.2 Extending M2T transformation languages with Signatures.

Given a template-based M2T language with the execution model described in Section 2.2.2.4, an extension to provide source-incrementality via signatures involves the addition of the following three concepts:

- A ***Signature*** is a value that consistently represents the text generated by a *TemplateInvocation*, and is used by a source incremental transformation engine to determine whether or not a *TemplateInvocation* needs to be re-evaluated.

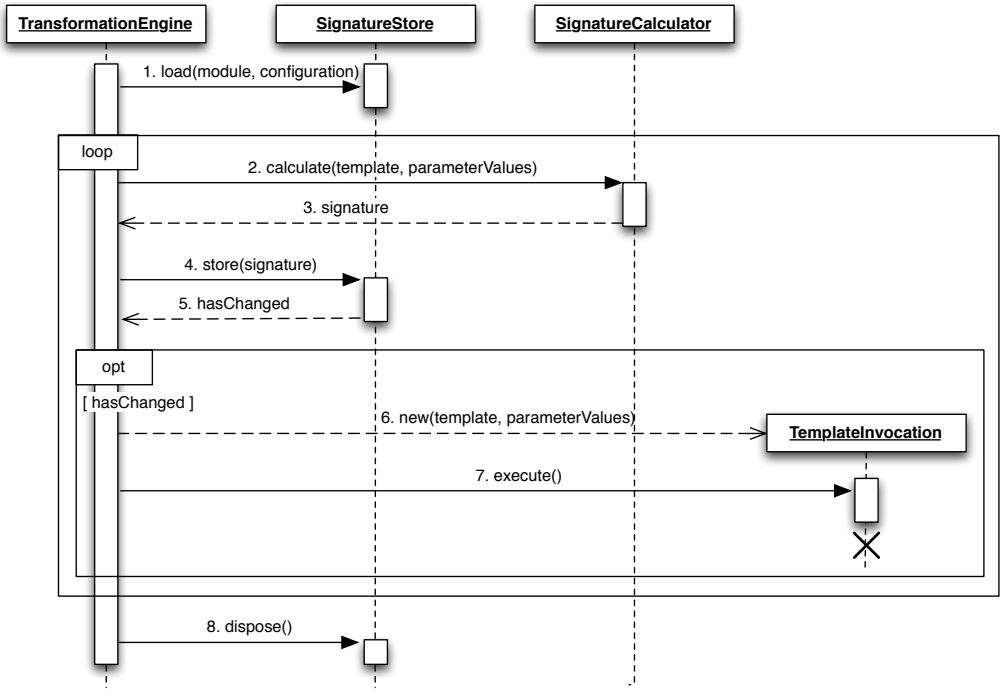


FIGURE 4.1: UML sequence diagram describing how Signatures are used to determine whether or not a TemplateInvocation should be executed.

- A ***SignatureCalculator*** is an algorithm for computing a Signature from a *TemplateInvocation*. The choice of algorithm for calculating signatures is left to the implementor, but two suitable algorithms have been designed and implemented (Section 4.4). Note that any algorithm for calculating a signature must be less computationally expensive than executing the *TemplateInvocation* (i.e., producing the generated text from the template), otherwise the time gained through incrementality will diminish as a non-incremental execution will execute faster than the incremental execution.

- A ***SignatureStore*** is responsible for storing the Signatures calculated during the evaluation of a M2T transformation, and makes these Signatures available to the transformation engine during the next evaluation of the M2T transformation on the same source model. The way in which Signatures are stored is left to the implementor, but some possible solutions are flat files, an XML document, or a database. A *SignatureStore* must be capable of persisting Signatures between invocations of a M2T transformation (in non-volatile storage). Moreover, a *SignatureStore* must be efficient: any gains achieved with a source incremental engine might be compromised if the *SignatureStore* cannot efficiently read and write Signatures.

Adding support for signatures to a template-based M2T language involves extending the transformation engine with additional logic that invokes a *SignatureCalculator* and a *SignatureStore* (Figure 4.1). During initialisation, the transformation engine requests that the *SignatureStore* prepares to access any existing *Signatures* for the current M2T transformation (*Module*) and the current *Configuration* (i.e., source model, file system location for the generated files, etc). Whenever the transformation engine would ordinarily create a *TemplateInvocation* from a *Template* and a set of *ParameterValues*, it instead asks the *SignatureCalculator* to calculate a ***Signature*** from the *Template* and *ParameterValues* (step 2). The transformation engine stores the *Signature* using the *SignatureStore* (step 4). The *SignatureStore* returns a Boolean value (*hasChanged*) which indicates whether or not the *Signature* differs from the *Signature* already contained in the *SignatureStore* from any previous evaluation of this M2T transformation (step 5). If the *Signature* has changed, a *TemplateInvocation* is created and executed (steps 6 and 7). The transformation engine informs the *SignatureStore* (step 8) when the transformation completes, so that it can write the *Signatures* to non-volatile storage.

4.3 Signature Calculation Strategies.

As briefly discussed above, a *SignatureCalculator* is an algorithm for computing a *Signature*. The remainder of this section describes two calculation algorithms: *automatic* and *user-defined*. In both cases, *Signature* values comprise (i) data obtained from the *ParameterValues* and *Template* (as discussed below), and (ii) a hash of the *Template*. The latter is included to ensure that the transformation engine can detect and re-execute templates that have been modified by the transformation developer.

4.3.1 Automatic Signatures.

A straightforward algorithm for calculating signatures is to concatenate the text generated by evaluating only the dynamic sections of a template, ignoring any static sections and any file output blocks. This algorithm is likely to be less computationally expensive than a typical evaluation of the template because fewer statements are evaluated and no disk access is required. For example, consider the templates shown in Listing 4.1, the automatic signature calculation algorithm would compute signatures from the dynamic sections of the templates (*personToDiv* and *tweetToDiv*), which is equivalent to the code in Listing 4.2.

```
1
2  // Signature personToDiv(p : Person)
3  [template public personToDiv(p : Person)]
4  [file (p.name)/]
5  <div>
6    <p>Number of followers: [p.followers->size()/]</p>
7    <p>Number of following: [p.follows->size()/]</p>
8    <h2>What's trending in your network?</h2>
9    [for(f : Person | p.followers)]
10     [for(t : Tweet | f.tweets)]
11     [t.hashtag/]
12     [/for]
13   [/for]
14 </div>
15 [/file]
16 [/template]
17
18 // Signature for tweetToDiv(t : Tweet)
19 [template public tweetToDiv(t : Tweet)]
20 [file (t.hashtag)/]
21 <div>
22   Hashtag: [t.hashtag/]
23   Re-tweeted [t.retweets->size()/] times
24 </div>
25 [/file]
26 [/template]
```

LISTING 4.1: Example using automatic signatures for the personToDiv and tweetToDiv templates in Listing 2.2, specified in OMG MOFM2T syntax.

```
1
2  // Signature personToDiv(p : Person)
3  [template public personToDiv(p : Person)]
4  [file (p.name)/]
5  [p.followers->size()/]
6  [p.follows->size()/]
7  [for(f : Person | p.followers)]
8    [for(t : Tweet | f.tweets)]
9      [t.hashtag/]
10   [/for]
11 [/for]
12 [/file]
13 [/template]
14
15 // Signature for tweetToDiv(t : Tweet)
16 [template public tweetToDiv(t : Tweet)]
17 [file (t.hashtag)/]
18   [t.hashtag/]
19   [t.retweets->size()/]
20 [/file]
21 [/template]
```

LISTING 4.2: A stripped version which contains only the dynamic sections of the template in Listing 4.1, from which automatic signatures are computed for personToDiv and tweetToDiv templates.

The evaluation of the dynamic sections of the templates shown in Listing 4.2 will result in different signature values for every model element that each template is invoked upon. In other words, the signature value computed as a result of the invocation of *personToDiv* on person *p1* will be different from the signature value computed from the invocation of the same template on person *p2* and *p3*. Suppose that the *name* of person *p1* is changed from *p1* to *p_ 1*. When the transformation is next executed, a new

signature whose value differs from the value of the signature computed during an initial execution of the transformation is computed for the invocation of *personToDiv* on *p1* as a result of the modification of *p1*'s *name*. On the other hand, this model change does not affect the values of the signatures computed from the template invocation of *personToDiv* on persons *p2* and *p3*, nor does it affect the signature values computed from the template invocation of *tweetToDiv* on the tweet object (i.e., *t1*). Hence, only the template invocation of *personToDiv* is re-executed on *p1* by the transformation engine.

4.3.2 User-defined Signatures.

User-defined signatures is an alternative signature generation algorithm that allows transformation developers to specify the expressions that are used to calculate *Signatures*. User-defined signatures are implemented by adding additional language constructs to a M2T template language, which allows developers to explicitly specify signature expressions for templates. In contrast to automatic signatures, it is a less transparent (more intrusive) approach which relies heavily on the developer's in-depth knowledge of the transformation. Ideally, a user-defined signature accesses precisely the same model elements (and precisely the same properties of those model elements) as the template for which the signature is a proxy. The responsibility for ensuring the signatures are representative of the templates rests with the transformation developer.

User-defined signatures can be more lightweight than automatic signatures. Since automatic signatures are computed from the dynamic sections of templates, they often comprise all model element features that are accessed in templates, and their sizes are dependent on the size of the output of individual dynamic sections, and the proportion of dynamic sections in the templates. On the other hand, user-defined signatures can be more precise and concise because they can include only model element features which the transformation developer considers the transformation to be sensitive to. Moreover, user-defined signatures give more control to the developer than automatic signatures. Given the transformation developer's knowledge of the transformation, fewer model element features which are most liable to modification, can be specified in a user-defined signature expression.

For example, for the transformation in Listing 4.3 user-defined signatures are used on lines 3 and 20. Each signature computed from these two lines accesses the same model element features that are accessed during the execution of the respective template. The signature expression instructs the transformation engine to compute the signature using the expression provided by the developer. The signature when the

```
1  // User-defined signature personToDiv(p : Person)
2  [template public personToDiv(p : Person)]
3  [signature : Sequence{p.handle, p.followers, p.follows, p.followers.tweets.collect()}]
4  [file (p.handle)/]
5  <div>
6    <p>Number of followers: [p.followers->size()/]</p>
7    <p>Number of following: [p.follows->size()/]</p>
8    <h2>What's trending in your network?</h2>
9    [for(f : Person | p.followers)]
10     [for(t : Tweet | f.tweets)]
11       [t.hashtag/]
12     [/for]
13   [/for]
14 </div>
15 [/file]
16 [/template]
17
18 // User-defined signature for tweetToDiv(t : Tweet)
19 [template public tweetToDiv(t : Tweet)]
20 [signature : Sequence{t.hashtag, t.retweets.collect()}]
21 [file (t.hashtag)/]
22 <div>
23   Hashtag: [t.hashtag/]
24   Re-tweeted [t.retweets->size()/] times
25 </div>
26 [/file]
27 [/template]
```

LISTING 4.3: Example of user-defined signature in a template-based M2T transformation, specified in OMG MOFM2T syntax.

personToDiv template is executed on person *p1* (in Figure 2.7(b)) will evaluate to `Sequence{{“p1”},{},{“p2”},{}}`, which is a complete reflection of the property accesses made in the template. Although the computed signature value is equivalent to the signature generated using the automatic signature generation strategy, the user-defined signature expression could also have included fewer model element properties which the developer knows are most susceptible to changes. In this case, the developer must ensure the inclusion of all model element features whose modification are likely to require re-execution of the template. The user-defined signature strategy is likely to be more time-efficient than the automatic signature strategy, because no analysis or invocation of a template is necessary to calculate signatures. Section 4.5 provides detailed comparison of automatic and user-defined signatures.

4.4 Implementation of Signatures in EGL.

To evaluate the efficacy of our approach, we extended a contemporary M2T transformation language, the Epsilon Generation Language (EGL), with support for signatures. EGL was chosen because it follows the typical template-based M2T execution mode (outlined in Section 2.2.2.2), and hence was suitable for extension to support signatures. Moreover, EGL is an active, open source project that is maintained by the two supervisors (Dr. Louis Rose and Dr. Dimitris Kolovos) of this research project.

4.4.1 Extending EGL with Signatures.

The modifications applied to EGL to support signature-based source incrementality follow the design described in Section 4.2. The implementation includes a *Signature-Calculator* that uses either automatic or user-defined signatures (Section 4.3).

Similar to the description of the execution of a M2T transformation in Section 2.2.2.4, in EGL, the transformation engine creates *RuleInvocations* by looping through a set of model elements that are of the same type as the context type specified in a rule. Using the automatic signature generation strategy, as the transformation engine executes a template on a model element, it creates a *Signature* object and computes the value of the signature by concatenating the text outputs of the evaluation of the dynamic sections of the template. On the other hand, using the user-defined signature calculation strategy, the signature is computed by evaluating the signature expression specified in the transformation rule. The signatures values are pairs of the form `< e, s >`, where e is the model element represented by its unique id within its container model, and s is the signature, which is a list of Strings. After the completion of the transformation execution, signatures are persisted in non-volatile store (*SignatureStore*).

Our implementation provides two types of *SignatureStore*: one persists *Signatures* in a relational database, and the other in a set of XML documents. Initial experimentation has shown that relational database store typically outperforms the XML store. Our *SignatureStore* assumes that parameter values can be serialised. For example, we assume that model elements have identifiers, so that we can avoid storing model elements in our *SignatureStore*. We defer responsibility for providing identifiers for model elements to the underlying modelling technology (e.g., plain XML, EMF). To date, we have used our EGL implementation with modelling technologies that can identify

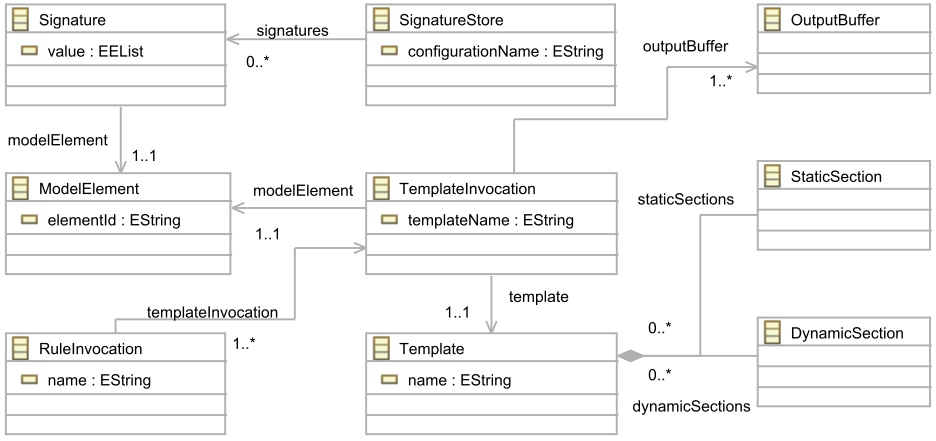


FIGURE 4.2: Extended Module invocation in EGL.

elements via their position in a document (e.g., XPath for XML models) and that can identify elements via a generated UUID (e.g., XMI IDs for EMF models).

In addition to implementing the *SignatureStore*, we extend an EGL module by overriding the default output buffer[1] of EGL. The *OutputBuffer* provides methods for appending, removing text to/from the buffer, and for merging newly generated text with previously generated text. As described in Section 2.2.2.4, EGL provides a parser which generates an abstract syntax tree that comprises static and dynamic section nodes from a template. The *OutputBuffer* writes the output of both static and dynamic sections to memory. For automatic signatures, since only the content of the dynamic nodes are relevant for calculating and re-evaluating signature values, we modify the logic of the default *OutputBuffer* through a *DynamicSectionOutputBuffer* (see Figure 4.3). The *DynamicSectionOutputBuffer* overrides the *printdyn* method of *IOutputBuffer*, and appends the output of each dynamic section into a *SignaturesValueList*. The *SignaturesValuesList* pre-empts changes in signature values which are undetectable by performing only string comparisons.

Determining if a signature's value has changed is a string comparison operation, and the order in which each text that is part of a signature's value is stored is important, otherwise a string comparison might be inadequate to determine signature value changes. For instance, suppose an element's (*person*) signature is $person.height + person.age$. Assuming *person*'s height and age are 2 and 3 respectively, *person*'s initial signature will be "23". If *person* is later modified such that its height becomes an empty string and its age becomes 23, *person*'s new signature would be "23" (string concatenation of "" and "23"), which is the same as its previous signature. In order to ensure effective signature value comparison, each component of a signature is contained in a collection

[1]The OutputBuffer is an internal mechanism of EGL that is responsible for writing the results of the evaluation of template statements during template execution

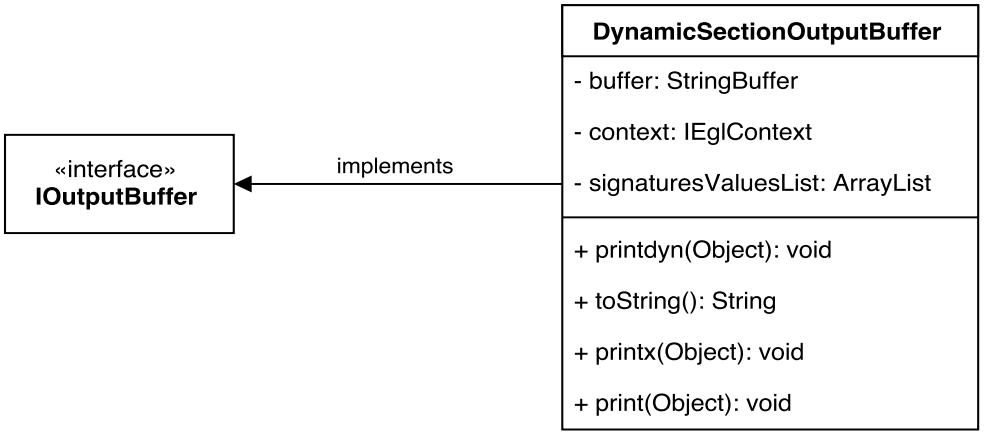


FIGURE 4.3: Extended OutputBuffer for Automatic Signatures.

(e.g., { “2”, “3”} compared to {“23”}) to mitigate against situations where a change in a model element's attributes would not alter its signature if the signature was stored as flat strings (e.g., “23”). Since more than one *RuleInvocation* can be created on the same model element during the execution of a transformation, the *SignatureStore* also stores information regarding rules (e.g., in the RDBMS implementation, rules were represented as table names). In other words, as depicted in Figure 4.2, each model element has a Signature with respect to each template that was executed against it. During subsequent executions of the transformation, the transformation engine retrieves the persisted signatures, and before re-executing a template on a model element, it computes a new signature for the model element, and it compares it with the stored signature value. The result of the comparison of the stored and newly computed signature values indicates as to whether the output of re-executing a template is likely to be different from the output that was previously generated when the template was last executed. If the newly computed signature value differs from the retrieved signature value, only then will the transformation engine re-execute the template.

Signatures Example.

To assess the practicality of signatures, this section demonstrates the use of, and results obtained from running a M2T transformation in EGL using automatic and user-defined signatures to provide source incrementality. Before going into detailed discussions about the execution of the transformation, a description of a M2T transformation scenario that could benefit from incremental transformation is provided. The transformation scenario is a contrived albeit realistic example which takes as input a model of a social network. Figure 4.4 represents a minimal model of persons on Twitter, showing the connections between each individual and their tweets. Connections between persons can be a ‘followed’ or ‘following’ relationship. However, the connections are not necessarily bi-directional, i.e., that *P1* follows *P3* does not mean *P3* is a follower of *P1*.

Suppose that when a person logs into their Twitter account, the Twitter home page has a section that displays a list of recent tweets or trending topics posted from persons directly connected to the person. Assume that the sections of the home page that displays lists of recent tweets and trending topics are automatically generated from the Twitter model via M2T transformation. It is conceivable that from time to time, a person's network of followers and followings will change, as such the contents of the web page section that displays the tweets from a person's followers will require re-generation. This represents an ideal situation for incremental M2T transformation as some execution time can potentially be saved by only re-generating contents for persons whose connections or tweets from their connections have changed. The example in this section is based on this scenario.

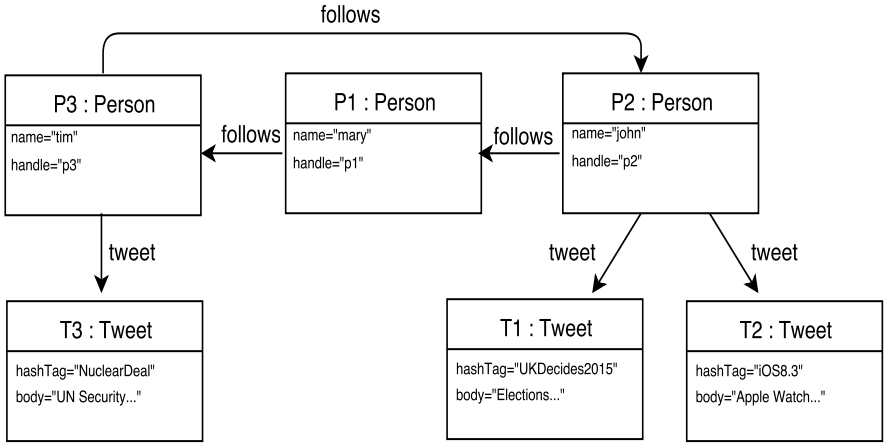


FIGURE 4.4: Example input model for the transformation in Listing 4.4.

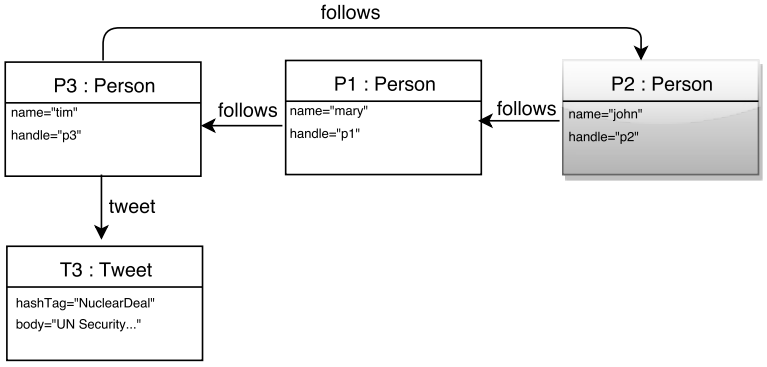


FIGURE 4.5: Evolved input model.

```
1
2  rule PersonToTweets
3    transform aPerson : Person {
4      template : "PersonToTweets.egl"
5      target : aPerson.name + ".txt"
6    }
```

LISTING 4.4: Example of an EGX M2T program.

Automatic Signature Execution.

Listing 4.4 is an EGX program that defines one transformation rule: *Person2Tweets* which is invoked to generate the contents of a section of a web page. The minimal version of the input model consumed by the EGX program is shown in Figure 4.4 which conforms to the metamodel in Figure 2.7(b) and consists of three Person objects and three Tweet objects. The template (Line 4) specified in the EGX program (Listing 4.4) is shown in Listings 4.5.

During the first execution of the transformation, three *RuleInvocations* are created on each person object (i.e., P1, P2, P3) in the input model. The transformation engine will query the *SignatureStore* to retrieve any previously stored signatures that

```
1
2  <div>
3    <h2>What's trending in your Group?</h2>
4    [% for (Tweet t in aPerson.followers.tweets) { %]
5    [%= t.hashTag %]
6    [% } %]
7  </div>
```

LISTING 4.5: Example of an EGL template used in Line 4 of the EGX program in Listing 4.4.

emanated from the same transformation. Table 4.1 shows the results of executing the transformation. Since it is the first execution of the transformation, none of the related model elements (in this case, Person objects) have a stored signature. Therefore the transformation computes signatures for each *Person* object by concatenating the text output from the text-emitting dynamic sections of the template, and generates three files from all Person objects. The template (Listing 4.5) has only one text-emitting dynamic section (i.e., [%= t.hashTag %]).

Model Element	Rule	Prev. Signature	New Signature	Template
P1	PersonToTweets	-	{ {{UKDecides2015},{iOS8.3}} }	PersonToTweets.egl
P2	PersonToTweets	-	{ {{NuclearDeal}} }	PersonToTweets.egl
P3	PersonToTweets	-	{ {{}} }	PersonToTweets.egl
			Number of files generated: 3	

TABLE 4.1: Table showing signatures generated using Automatic generation strategy during the first execution of the transformation.

Assume the input model is modified such that *Person P2*'s tweets *T1* and *T2* are deleted as shown in Figure 4.5. Following this change, the transformation engine computes new signatures for each Person object and compares the new signature values with the previously stored signature values. As depicted in Table 4.2, only *Person P1*'s signature is affected by the change that was applied to the input model. Thus only the file generated from *Person P1* is re-generated.

Model Element	Rule	Prev. Signature	New Signature	Template
P1	PersonToTweets	{ {{UKDecides2015},{iOS8.3}} }	{ {} }	PersonToTweets.egl
P2	PersonToTweets	{ {{NuclearDeal}} }	{ {{NuclearDeal}} }	PersonToTweets.egl
P3	PersonToTweets	{ {{ }} }	{ {{ }} }	PersonToTweets.egl
			Number of files generated: 1	

TABLE 4.2: Table showing signatures generated using Automatic generation strategy after modifying the input model.

Limitations of Automatic Signatures.

Despite limiting the re-execution of a transformation to only parts of the transformation that are affected by changes (as seen in the previous section), and potentially

reducing the execution time of transformations, this algorithm does not always produce signatures that are consistent with the text generated by their corresponding *TemplateInvocations*. A signature is consistent with a template if it completely reflects the variable parts of template. Computed signatures can be inconsistent when a dynamic section of a template does not contribute text to the contents of a generated file, but is used to control the path of the template's execution. For example, consider the template in Listing 4.6. Here, the $aPerson.tweets.size$ feature indirectly contributes to the generated text. The *Signature* calculated by the automatic algorithm would be equivalent to evaluating the 'hashTags' of tweets of *aPerson*'s followers, which is not sensitive to all possible changes to a Person object that can result in a different text being generated. Suppose that the model evolves as described in the previous section, the signature of *Person P1* using automatic signature generation will remain unchanged despite the change to the model, and the obvious need to re-generate the text file for *Person P1* because the transformation engine using automatic signatures cannot detect the change to the number of followers a person object has, and thus, no template invocation is performed.

User-defined Signature Execution.

The transformation example described in the previous section can be modified to use user-defined signature calculation strategy by adding the following code: ($[signature : Sequence\{aPerson.followers.tweets.hashtag\}]$) to the EGX program in Listing 4.4. The evaluation of this user-defined signature expression will result in exactly the same signatures (as shown in Table 4.3) that were computed using the automatic generation strategy since the expression includes all model element features that are accessed in the template. Also, when the transformation is re-executed on the evolved input model, a similar outcome will be obtained - only one file will be re-generated.

```
1
2  <div>
3    <h2>What's trending in your network?</h2>
4    [% for (Tweet t in aPerson.followers.tweets) { %]
5    [%= t.hashTag %]
6    [% } %]
7    [% if(aPerson.tweets.size() == 0 ) { %]
8    You have no tweets of your own.
9    [% } else { %]
10   You have some tweets of your own.
11   [% } %]
12 </div>
```

LISTING 4.6: Use of a dynamic section to control the flow of execution, which causes the automatic signature calculation strategy to produce a non-consistent signature.

The remainder of the discussion in this section will focus on how user-defined signatures can be used to address the inability of automatic signatures to produce signatures that are sensitive to model element features whose values are not directly part of the generated text. Given the template in Listing 4.6 which the automatic signature finds problematic because of the model element feature access in the conditional statement (line 7), a user-defined signature can be applied to generate signatures that will be sensitive to all possible relevant changes to the input model. For instance, the signature expression (line 4 of Listing 4.7) includes a collection of a person's tweets, and the 'hashTags' of tweets by a person's followers. The computed signatures before and after the input model is modified are shown in Tables 4.3 and 4.4 respectively.

```
1
2  rule PersonToTweets
3    transform aPerson : Person {
4      signature : Sequence{aPerson.followers.tweets.hashTag + aPerson.tweets.isEmpty()}
5      template : "PersonToTweets.egl"
6      target : aPerson.name + ".txt"
7  }
```

LISTING 4.7: Example of an EGX M2T program using User-defined signature to address insensitive automatic signatures.

Model Element	Rule	Prev. Signature	New Signature	Template
P1	PersonToTweets	-	{ {{UKDecides2015},{iOS8.3}},True }	PersonToTweets.egl
P2	PersonToTweets	-	{ {{NuclearDeal}},False }	PersonToTweets.egl
P3	PersonToTweets	-	{ {{ }},False }	PersonToTweets.egl

Number of files generated: 3

TABLE 4.3: Table showing signatures generated using User-defined generation strategy during the first execution of the transformation.

Model Element	Rule	Prev. Signature	New Signature	Template
P1	PersonToTweets	{ {{ UKDecides2015 },{iOS8.3}},True }	{ {{ }},True }	PersonToTweets.egl
P2	PersonToTweets	{ {{NuclearDeal}},False }	{ {{NuclearDeal}},True }	PersonToTweets.egl
P3	PersonToTweets	{ {{ }},False }	{ {{ }},False }	PersonToTweets.egl

Number of files re-generated: 2

TABLE 4.4: Table showing signatures generated using User-defined generation strategy after the input model is modified.

As seen in Table 4.4, the computed user-defined signatures are sensitive to the changes applied to the input model despite the model feature access in the conditional statement in Listing 4.6. As such, files are re-generated from person *P1* and person *P2*. The automatic signature strategy on the other hand would have resulted in the regeneration of the file from only *P1* crucially skipping regeneration of the file from *P2* because it would have been unaware of the deletions of tweets *T1* and *T2*.

Limitations of User-defined Signatures

Despite the effectiveness of user-defined signatures at addressing the incompleteness of

automatic signatures, they are not without drawbacks. Obviously, the specification and maintenance of correct signatures can be difficult for large and complex transformations, requiring human time and effort. User-defined signatures are also prone to human error. For example, a transformation author might specify a signature expression that is incomplete. An incomplete signature expression omits at least one property access made in the template, and cannot be relied upon to produce signatures that are true reflections of the property accesses made in a template. A correct signature captures all necessary property accesses in a template and is sensitive to changes to the model that will alter the output of a template.

Furthermore, writing signature expressions for templates that access a large number of model element properties can result in very long lists of attributes in the signature expression, which may be difficult to manage. The prospect of having to manually scan through a long list of properties in a signature expression to check the expression's completeness can be daunting.

We address these challenges by applying runtime analysis of templates to provide helpful hints to the developer, which the developer can use to assess the correctness and completeness of their signature expressions.

4.4.2 Runtime analysis for User-defined Signatures

As discussed in Section 3.2.2, contemporary M2T languages limit the applicability of static analysis techniques to the languages, because most M2T languages are dynamically typed and support features such as dynamic dispatch [120]. We have applied runtime analysis of templates to determine model element properties accessed in a template during transformation execution. The runtime analysis compares the model element features which make up a user-defined signature expression with the model element features that are actually accessed within a template. If the model element features accessed during template execution differ from the model element features contained in signature expression, the transformation engine can notify the developer of the potentially incomplete signature expression. For example, if a template accesses the *name* of a person *p1*, and the user-defined signature expression for the template does not include *p1.name*, the transformation can flag this off as a potential omission by the developer. These notifications are useful hints to the developer for assessing the correctness and completeness of the specified signature expression composition. Model element feature access hints are particularly useful during the initial transformation execution, because the first transformation execution is not incremental, but the hints

help the developer to immediately assess the signature expression, perhaps still with limited knowledge of the transformation.

In addition to this, property access hints can capture model element property accesses used to control template execution flow. For instance, in the example shown in Listing 4.6, the runtime analysis will capture and suggest to the developer to include 'person.followers' in the signature expression.

4.4.3 Feature-based User-defined Signatures

Given the difficulty of specifying signature expressions that can generate complete and correct signatures, and the challenge of maintaining such expressions in the face of an evolving complex model, writing user-defined signature specifications could be aided by providing syntactic shortcuts that can be used to concisely generate a signature for a model element.

A feature-based user-defined signature derives signature values by serialising a model element: all of the attribute and reference values contained in the model element are converted into a collection of strings. For primitive attribute types, the feature-based signature method returns the string literal of the attribute, while for object type attributes and references, it recursively traverses the object tree returning the signature of each object (see implementation details in Appendix C). For example, invoking the feature-based signature method on person *p1* in the input model (Figure 4.4) will result in the generation of the following signature `Sequence{{‘‘p1’’},{‘‘Mary’’},{‘‘p3’’},{‘‘p2’’}}`.

Feature based user-defined signatures guarantee that all possible structural feature changes to a model element are captured in the signature value. However, it can also result in full traversals of input models, particularly if there is much inter-dependency between model elements. Traversing every model element in the process of computing the signature for a single model element can be very costly. In order to prevent the traversal of an entire model, the algorithm is restricted to model element references that are at the same hierarchical level in the model tree. Another potential downside of the feature-based signature method is that because it traverses all structural features of a model element, the computed signature value of a model element will include features which may not contribute directly or indirectly to the text generated from a model element. In this case the feature-based signature method causes the signature approach to be pessimistic, resulting in re-generation of files without new or different contents.

Although the feature-based signature method can cause the transformation engine to perform additional computation compared to a user-defined signature expression, from

the perspective of a developer its a more convenient method because it allows a more concise specification of user-defined signature expressions.

4.5 Discussion

In the previous sections, we described how M2T languages can be extended with signatures to achieve source-incrementality. In this section, we will elaborate on the differences that exist between automatic and user-defined signatures.

Recall that the applicability of automatic signatures is limited to templates which do not make model element property accesses in ways that the accessed model element properties do not directly contribute text to the output of the template. User-defined signatures, when specified correctly, are capable of detecting changes to all model element properties even when they are accessed within conditional statements. An advantage of user-defined signatures over automatic signatures is that they can contain more information which makes them more sensitive to model element property changes (e.g., model element properties used to direct template execution paths).

Since user-defined signatures are computed from expressions which are more specific (i.e., they contain only model element properties whose modification may alter the output of a template), it is conceivable that these expressions will execute faster than automatic signatures which are computed from dynamic sections of templates. Automatic signatures are less concise because they can potentially include duplicate model queries since it is possible for multiple dynamic sections to access the same parts of an input model. Moreover, the dynamic sections of a template may also include other transformation parameters that are executed along with the model queries, which may result in longer execution time compared to executing only model queries in user-defined signature expressions.

Furthermore, automatic and user-defined signatures differ from a usability perspective. Automatic signatures are transparent to the transformation developer and do not require user intervention (i.e., there is no additional effort in specifying them, and ensuring their correctness), and as such, they are not prone to human error. In contrast, user-defined signatures are prone to human error but afford the developer more control.

4.6 Summary

This chapter presented a novel approach, termed *Signatures*, for providing source incrementality in M2T languages. By combining runtime impact analysis and constraint-based change detection, signatures restrict the re-evaluation of template invocations to subsets of the transformation that are affected by model changes. Hence, it reduces pessimism and improves source-minimality. Since impact analysis is performed at runtime, it is context-aware (i.e., link between template invocation and model element is known), only the changes that are relevant to the transformation are detected. A demonstration of the *Signatures* technique was provided through an incremental M2T generation of text from a model representing a social network. The implementation of the Signatures technique on top of the EGL M2T language has demonstrated the feasibility of the technique and its portability to other contemporary M2T languages such as Acceleo or Xpand. Two strategies (automatic and user-defined) for generating signatures were presented. Automatic signatures compute signatures from the dynamic sections of templates. User-defined signatures require transformation developers to specify expressions from which signatures are computed.

An important limitation of the automatic signature generation strategy was discussed along with how user-defined signatures can be used to address the limitation. A complete evaluation of the technique is given in Chpater 6, which contains the results of empirical evaluation of the signatures method using well developed case studies.

Given the shortcomings of the automatic signature generation strategy and the challenges associated with specifying correct user-defined signature expressions, the next chapter will present another novel technique (Property Access Traces) for source incrementality which is based on the analysis of transformation execution traces. Unlike user-defined signatures, the use of property access traces is fully automated and is not limited by the shortcomings of signatures.

Chapter 5

Property Access Traces

In Chapter 3 we identified source incrementality as an important criterion for an incremental transformation engine, and in the previous chapter, we proposed a novel approach (*Signatures*) for providing source-incrementality in M2T languages. However, through an example, we also highlighted the shortcomings of signatures, which are: automatic signatures can be insensitive to changes to model elements that do not directly contribute text to the output of a template; user-defined signatures can be difficult to define and manage. This chapter presents another novel technique - *property access traces* that does not demonstrate these shortcomings. The work on *property access traces* was published in [121].

Property access traces contain concise and precise information collected during the execution of a M2T transformation and can be used to detect which templates need to be re-executed in response to a set of changes in the input model(s). Instead of re-evaluating a template, the transformation engine evaluates the property accesses that were obtained from the last successful execution of a transformation. The basis of this approach is that the process of evaluating property accesses is a computationally less expensive operation compared to re-evaluating a template.

Section 5.1 provides an overview of the *property access trace* technique. Section 5.2 describes the major concepts that make up the *property access traces* technique and discusses the way in which an existing template-based M2T language (i.e., EGL) can be extended with support for property access traces. Section 5.4 describes property access traces in an offline mode, when the transformation engine is required to determine model changes at runtime. Section 5.5 discusses the use of property access traces in an online mode to achieve immediate propagation of changes as they occur in the input model, as well as how instant change detection is realised in the online mode. Additionally, Section 5.6 provides a discussion about the differences between offline

and online transformation executions using property access traces, and also highlights conditions under which property access traces cannot be relied upon to provide source-incrementality. Section 5.7 discusses the limitations of property access traces. Finally, Section 5.8 concludes the chapter by summarizing the practicability, as well as the limitations of the technique introduced in this chapter.

5.1 Overview

Property access traces provide a lightweight and effective mechanism for recording an M2T transformation's execution information which can be then used to detect relevant changes in the source model, and to determine which parts of the transformation need to be re-executed against which model elements. When a transformation is first executed, model element property accesses are recorded and persisted in non-volatile storage. A *property access trace* contains properties of model elements that are accessed during transformation execution, and maps them to the property accesses to the template invocations that triggered them. In subsequent executions of the transformation, the property access trace is used to detect whether the source model has changed, and to re-execute only template invocations that are potentially affected by those source model changes.

In contrast to automatic signatures which can be insensitive to changes to model elements features that contribute to template execution control flow, but not to the output, property access traces can automatically detect changes of interest to model elements features regardless of whether the features contributes text to a template's output or not. Furthermore, unlike automatic signatures (Chapter 4) which are computed from expressions (which may include parameters other than model element properties) contained in the dynamic sections of templates, property access traces are more precise and only record data from the execution of model queries. For example, the signature computed from this statement [% = *title.concat*(*aPerson.name*)%], is the returned value of concatenating the value of a template variable (*title*) with the value of a model element's property (*aPerson.name*), whereas a property access trace is computed from only the model element property contained in the expression, in this case (*aPerson.name*).

Property access traces can be applied to a transformation language to provide incrementality in one of two modes: online, and offline. In the offline mode, the transformation engine terminates after an execution, and re-executes a transformation only when a new version of the input model is available. However, as will be discussed in Section 5.5, it is also possible to apply property access traces to enable immediate change propagation

(online transformation). In the online transformation mode, a transformation engine can re-execute a transformation as the changes occur in its input model(s). Although both modes are founded on the same principle, there are subtle differences between the two modes. For example, the online mode requires that the transformation engine has access to model changes without having to perform change detection, while in offline mode, the transformation engine performs change detection. The remainder of this chapter introduces the general principles of property access traces, and then discusses the offline and online modes in detail.

5.2 Design

Supporting property access traces involves extending the execution engine of a M2T language with four new concepts. Property access traces comprise transformation information that is derived from model elements and from the templates that are invoked on those model elements. A *PropertyAccessRecorder* observes the execution of a template, capturing information about which parts of the input model are accessed by the template. We use the term *PropertyAccess* to refer to the information captured by a *PropertyAccessRecorder*, and give a more precise for *PropertyAccess* below. The recorded *PropertyAccess(es)* which make up a *PropertyAccessTrace* are then persisted in non-volatile storage by a *PropertyAccessStore*. Figure 5.1 illustrates the conceptual organisation of the information contained in a *PropertyAccessTrace*.

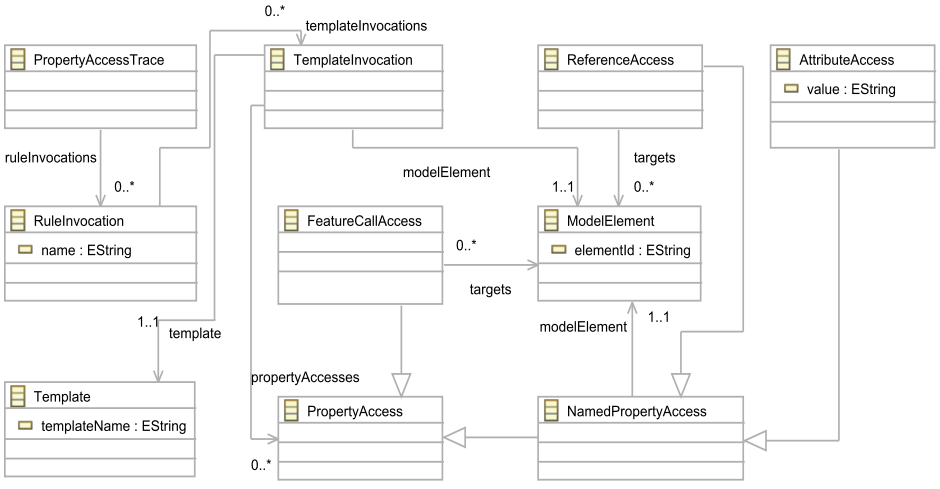


FIGURE 5.1: Overview of Property Access Trace.

- A ***PropertyAccess*** is a triple of the form `< e, p, v >`, where e is the unique identifier[1] of the model element, p is the name of the property, and v is the value of the property. The way in which model element identifiers are computed varies, depending on the underlying modelling technology (e.g., XMI IDs or relative paths for EMF XMI models). There are two types of property accesses – *NamedPropertyAccesses* and *FeatureCallAccesses*. *NamedPropertyAccesses* are derived from direct operations on model elements, and they are classified by the type of model element feature (i.e., *AttributeAccesses* and *ReferenceAccesses*) that is accessed and the type of value that they store. *AttributeAccesses* store a string value and are used when the accessed property type is a primitive. An *AttributeAccess* is derived when a model element's feature is accessed in a template (e.g., the execution of this statement: *person.name*). *ReferenceAccesses* store the unique identifiers of the referenced model elements and are obtained when the feature of a model element that is accessed is an association between two classes or between two instances of a class (e.g., person.followers). Lastly, a *FeatureCallAccess* is derived from expressions that access instances of a metamodel type, rather than properties of a model element (e.g., Person.all, Person.allInstances). *FeatureCallAccesses* return a collection that contains the unique identifiers of the objects.

- A ***PropertyAccessTrace*** (Figure 5.1) captures which transformation rules are invoked on which source model elements and, moreover, which *PropertyAccess*es resulted from each invocation of a transformation rule (a *RuleInvocation)* in Figure 5.1).

- A ***PropertyAccessRecorder*** is responsible for recording *PropertyAccesses* during the execution of a template, and for updating the *PropertyAccess*es when a change in the value of a *PropertyAccess* is detected. It is important to note that since property access traces contain data about input model elements only, changes to the transformation specification are not considered (See section 5.7 for a discussion on known limitations of this approach).

- A ***PropertyAccessStore*** is responsible for storing the *PropertyAccesses* provided to it by the *PropertyAccessRecorder*. The *PropertyAccessStore* is also responsible for making *PropertyAccesses* (that were stored during a previous transformation execution) available to the transformation engine. We use an embedded RDBMS to store *property accesses*, but other options (e.g., graph databases, XML documents, etc.) are also possible. A *PropertyAccessStore* must be capable of persisting, in non-volatile storage, the property access trace information between

[1] uniquely identifies a model element in its containing model

invocations of a M2T transformation. The main requirement for a *PropertyAccessStore* is performance: any gains achieved with a source incremental engine might be compromised if the *PropertyAccessStore* cannot efficiently read and write property access traces.

During the initial execution of a transformation, the *PropertyAccessRecorder* creates *PropertyAccesses* from the features of model elements that are accessed during the execution of each rule. The collected *PropertyAccesses* are organised by *RuleInvocation* by the transformation engine to form a *PropertyAccessTrace* and stored by the *PropertyAccessStore*. When changes are then made to the input model(s), in subsequent executions of the M2T transformation, the transformation engine retrieves the previous *PropertyAccessTrace* from the *PropertyAccessStore*. Whenever the transformation engine would ordinarily invoke a transformation rule, it instead retrieves each relevant *PropertyAccess* from the *PropertyAccessTrace* and queries the model to determine if the value of any of the *PropertyAccesses* has changed. Only when a value has changed is the transformation rule invoked. The *PropertyAccessTrace* is updated and stored if any values have changed.

5.3 Extending EGL with Property Access Traces

In order to demonstrate the feasibility of *property access traces*, we extended a template-based M2T language (EGL) [11]. The modifications applied to EGL to support source-incrementality based on property access traces follows the design described in Section 5.2.

EGL's transformation engine inherits an internal *ExecutionListener* from EOL (see Section 2.1.7). The *ExecutionListener* provides two methods: *aboutToExecute* and *finishedExecuting*, both of which take as part of arguments an abstract syntax tree (AST) of an EOL statement (e.g., ASTs derived from parsing a template and translating each statement to an EOL equivalent). In order to record property accesses on model elements during template executions, a *PropertyAccessExecutionListener* extends the default *ExecutionListener*, and can capture model element based property access executions including the model element id, property name, and the result of the execution of the AST in the *finishedExecuting* method. The *PropertyAccessExecutionListener* triggers execution notifications to the instances of *PropertyAccessRecorder* accessed through an *EgxModule*. The code snippet in Listing 5.1 demonstrates how the *PropertyAccessExecutionListener* can be utilised to record property accesses during a template execution.

```
module.getContext().getExecutorFactory().addExecutionListener(new IExecutionListener() {
  Object type = null;

  @Override
  public void finishedExecuting(AST ast, Object result, IEolContext context) {
    if (ast.getType() == EolParser.POINT) {
      if (isAllInstances(ast) && type instanceof EolModelElementType){
        FeaturePropertyAccess featureCallSpa = new FeaturePropertyAccess(((
     EolModelElementType) type).getName(), ast.getSecondChild().getText());
        featureCallSpa.setPropertyValue(Integer.toString(((Collection<?>)result).size()));
        featureCallSpa.setElementId(((EolModelElementType) type).getName());
        featureCallStore.add(featureCallSpa);
      }
    }
    type = result;
  }
}
```

LISTING 5.1: Using ExecutionListener to record property accesses.

In addition to recording property accesses in templates, our implementation can monitor changes to transformation parameters defined outside, but accessed within templates. For example, there are some additional EGX language constructs that can access source models (such as `pre` and `post` blocks which are executed before and after the entire transformation). Recall that EGX (Section 2.2.2.4) is an orchestration sub-language of EGL which provides mechanisms for co-ordinating template execution. As shown in Listing 2.4, a transformation can define global variables in the *pre* and *post* blocks, which are then used during template invocations. It is important to note however, that not all templates would necessarily access the *pre* and *post* block variables. As such, changes to variables defined in these blocks present additional concerns for an incremental transformation engine. The first concern is detecting changes in the *pre* and *post* blocks, and the second concern is finding and re-executing only the templates that access the changed *pre* and *post* block variables.

The data recorded by the property access recorder constitutes an instance of a *property access*. Upon completion of the execution of the rule invocations, a mapping of model elements to template invocations, which in turn links to a set of property accesses is created. This precise data obtained during the transformation execution is the *property access trace*. The property access recorder transmits the property access trace to the *property access store* which is responsible for persisting the property access trace in non-volatile storage.

5.4 Offline Transformation in EGL.

In the offline mode, during the execution of a transformation in EGL, the transformation engine creates *RuleInvocations* by looping through all transformation rules and

executing template invocations on model elements of the same metamodel type as specified in the transformation rule. Since more than one *RuleInvocation* can be created on the same model element during the execution of a transformation, the *PropertyAccessStore* also stores information regarding transformation rules, such that each property access has links to respective template invocations and each template invocation to a rule invocation. It is important to note that templates often contain multiple accesses to the same model element feature. Therefore, in order to minimize the space requirements for persisting a property access trace, only unique property accesses are recorded.

During subsequent executions of the transformation, the transformation engine retrieves the persisted property access trace, and before re-executing a template on a model element, it examines the values of associated property accesses that were retrieved from the property access store by querying the input model to determine whether there has been any modification of any of the model element features that were accessed during the previous execution of the template. If the current value of at least one template invocation's property access differs from the retrieved value of such property access, only then will the transformation engine re-execute the template.

The execution of a transformation in the offline mode proceeds as follows:

1. Create and store a property access trace upon the first execution of the transformation.
2. Receive modified version of input model.
3. Retrieve stored property access trace.
4. Analyse retrieved property access trace to determine changes.
5. Re-execute template invocations affected by changes in input model.
6. Update property access trace based on re-executed template invocations.

After creating and storing property accesses from an initial transformation execution (step 1), the transformation engine, in subsequent transformation executions (receives a modified version of the input model in step 2), and retrieves the previous *PropertyAccessTrace* from the *PropertyAccessStore* (step 3). Whenever the transformation engine would ordinarily invoke a transformation rule, it instead retrieves each relevant *PropertyAccess* from the *PropertyAccessTrace* and queries the model to determine if the value of any of the *PropertyAccesses* has changed (step 4). Only when a value has changed is the transformation rule invoked (step 5). The *PropertyAccessTrace* is

updated and stored if any values have changed (step 6). Steps 5 and 6 are optional, as they only take place if the analysis in step 3 results in the re-execution of any template invocation.

5.4.1 Offline Transformation Execution Example.

The demonstration of the offline transformation in this section is based on the example M2T transformation that was presented in Section 4.4.1 (the listings and input model are repeated on this page for reader convenience). The transformation consists of an EGL template (Listing 5.2), and receives as input, a minimal model of a Twitter network (Figure 5.2). The template features the use of a model element property to direct its execution path, thus, the automatic signature calculation strategy could not be used to guarantee the computation of signatures that are sensitive to changes to model element properties that are accessed within conditional statements. This limitation of the automatic signatures led to the implementation of user-defined signatures. However, as discussed in Section 4.4.1 with the aid of the Twitter example, while user-defined signatures are capable of addressing the limitations of automatic signatures, they are not transparent to the developer and require in-depth knowledge of the transformation, and more effort in keeping the signature expressions up to date. In this section, we demonstrate offline transformation execution using property access traces and show that property access traces do not exhibit the limitations of the signatures technique.

During the first execution of the transformation, the transformation engine computes and stores the property access trace shown in Figures 5.6 and 5.3. When the M2T transformation is executed again, the transformation engine retrieves the property access trace, and queries the parts of the model that were previously accessed by the transformation, such as the hashtag of a tweet object. Only when the value of any property differs from the value stored in a property access is the containing rule invocation re-executed.

```
1
2  <div>
3    <h2>What's trending in your network?</h2>
4    [% for (Tweet t in aPerson.followers.tweets) { %]
5      [%= t.hashTag %]
6    [% } %]
7    [% if(aPerson.tweets.size() == 0 ) { %]
8      You have no tweets of your own.
9    [% } else { %]
10     You have some tweets of your own.
11   [% } %]
12 </div>
```

LISTING 5.2: Example of a template demonstrating the use of property access traces.

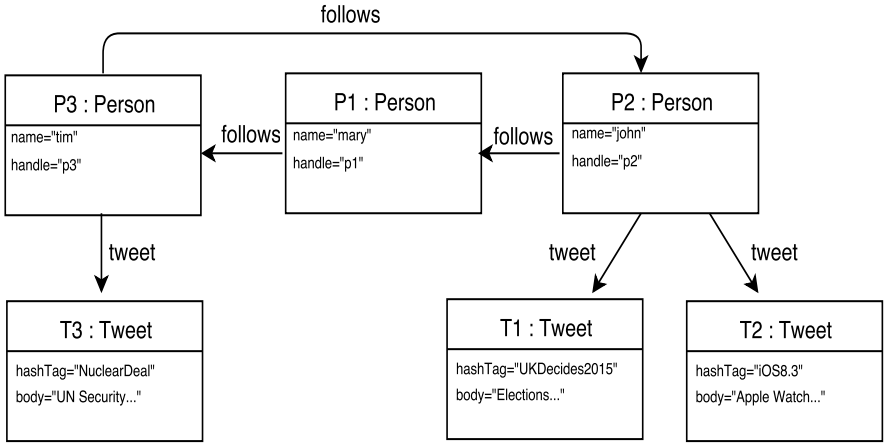


FIGURE 5.2: Example input model for the transformation in Listing 5.2.

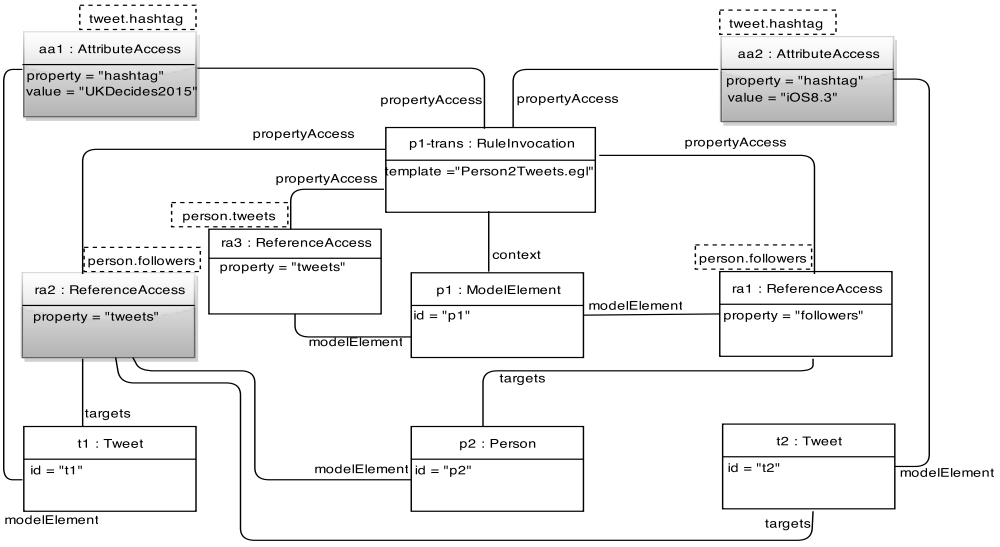


FIGURE 5.3: Expansion of the property access trace for the *p1-trans* rule invocation.

For example, the *p1-trans* rule invocation (Figure 5.3) indicates that if all of the following constraints hold, then the rule invocation needs not be re-executed:

1. `p1.followers == {p2}` – due to *ra1*
2. `p2.tweets == {t1, t2}` – due to *ra2*
3. `t1.hashtag == ‘‘UKDecides2015’’` – due to *aa1*
4. `t2.hashtag == ‘‘iOS8.3’’` – due to *aa2*
5. `p1.tweets == { }` – due to *ra3*

Note that the highlighted property accesses (i.e., `aa1`, `aa2`, `ra2`) in Figure 5.3 store the old values of these property accesses. After the input model is modified as shown

in Figure 4.5, whereby *t1* and *t2* are deleted, the transformation engine evaluates the constraints listed above. Of these constraints, conditions #2, #3, and #4 will no longer hold: *p2.tweets* will now evaluate to {} (empty list), and both *t1.hashtag*, *t2.hashtag* to null. Consequently, the transformation engine will re-execute the *p1-trans* rule invocation.

We have not shown the complete property access trace for the *p2* and *p3* rule invocations, but they are very similar in structure to the *p1-trans* rule invocation in Figure 5.3. The property accesses for *p2-trans* result in the following constraints:

1. `p2.followers == {p3}`
2. `p3.tweets == {t3}`
3. `t3.hashtag == ‘‘NuclearDeal’’`
4. `p2.tweets == {t1, t2}`

while the property accesses for *p3-trans* result in the following constraints:

1. `p3.followers == {p1}`
2. `p1.tweets == { }`
3. `p3.tweets == {t3}`

From these constraints, it is clear that the deletion of *t1* and *t2* does not require a re-execution of the *p3-trans* rule invocation as none of the constraints above depend on *t1* or *t2*, or any of their properties. An important advantage of using property access traces in offline mode over the *signatures* technique presented in chapter 4 is that the property accesses recorded during a transformation execution contain all model element features that are accessed in a template including accesses in conditional statements which makes them sensitive to all relevant model element changes.

5.5 Online Transformation in EGL

So far, we have assumed that M2T transformations are only re-executed when a new version of an input model is available, and we have demonstrated how *signatures* (Chapter 4) and *property access traces* can be used to limit the incremental re-execution of a transformation to only the template invocations affected by model changes. However,

so far, we have not considered scenarios where instant synchronisation of generated artefacts with changing input model may be more beneficial than waiting for the model editing to complete before the transformation is re-executed. An online transformation is one that enables synchronisation of generated artefacts with input models while the input models are being modified. Online transformation can be particularly important for modelling tools which require instant propagation of model changes to generated artefacts to ensure consistency. In this section, we discuss how property access traces can be used to support online transformations.

In offline M2T transformation we assume that the model editing process happens in a black box, and we can only have access to the latest version of the transformation's input model. However, modelling frameworks and tools commonly offer model-element-level change notification facilities (e.g. EMF's Notification framework) which can be leveraged to eliminate the need for post-fact change detection and facilitate online incremental M2T transformation. In the online transformation mode, the entire transformation context is maintained in memory and as changes are made to the input model, the changes are readily analysed to identify their impact, and relevant rule invocations are re-executed on the fly. For example, in projects where frequent, instant synchronisation and consistency checking are necessary. Commonly, modelling tools that are used to construct graphical editors for modelling languages (e.g., Eugenia [37]) perform M2T transformations which generate source code (e.g., implementation classes that adapt the model classes for editing) for the editor. For example, each time an input model is modified, Eugenia updates an intermediate model (*genmodel*) through a M2M transformation before re-executing the M2T transformation that generates the editor from the intermediate model. As the construction of a model editor involves several iterations which contain minor tweaks, immediate re-synchronisation of the editor code with the *genmodel* is desirable, and can potentially reduce development time, since the developer can instantly assess the effects of the changes on the model editor. Another important advantage of online change propagation is that theoretically, it is likely to be more time-efficient than the offline transformation mode because the transformation engine does not need to perform change detections, and hence, a complete traversal of the input model is not needed.

5.5.1 Design

Although online and offline transformation using property access traces are founded on the same principle, which is recording property accesses on model elements during template invocations and using the recorded data to limit the re-execution of a transformation to relevant template invocations, there exists subtle differences between the

two modes: 1. In the offline mode change detection is performed by the transformation engine in a batch mode, whereas in the online mode, the transformation engine is notified of model-element-level changes, and 2. Impact analysis in offline mode requires full model and property access trace traversals, while in online mode, only a subset of the property access trace is examined.

In the offline mode, change detection entails querying the input model to determine whether the values of relevant property accesses have changed. In the online mode, change notifications are provided by the underlying model editor. It follows that in the online mode, a property access does not need to include the value of the property since the transformation does not require this information to determine whether the value of a model element's feature has been modified or not. Therefore, a property access becomes a pair of the form $< e, p >$, where e is the model element id, p is the model element's property name.

Furthermore, online transformation introduces the notion that model element changes are external and an indirect concern of the transformation engine since the transformation engine does not have to compute them. Therefore, model element change is conceptualized as an external entity that is consumed by the transformation engine much like a transformation parameter. Hence, in addition to *PropertyAccessTrace*, *PropertyAccessRecorder*, *PropertyAccess*, and *PropertyAccessStore*, a further concept is introduced:

- A ***Change*** comprises a model element's id and the name of the property of the modified model element (i.e., a pair of the form $< e, p >$) and it is structurally equivalent to a property access. It is used to determine which rule invocations require re-execution.

An overview of online transformation using property access traces is presented in Figure 5.4. In online propagation mode, the execution of a transformation proceeds as follows:

1. The transformation engine determines which input models to observe.
2. The model editor triggers change notifications as the user edits the model.
3. The transformation engine receives change notifications for an input model as they occur.
4. The transformation engine analyses the change notifications to find relevant rule invocations.

5. The transformation engine re-executes related rule invocations.

Since a transformation configuration may contain more than one input model, in step 1, before the initial execution of a transformation, the transformation engine determines which input models are relevant to the transformation. Typically, these are models that are loaded into the transformation context. In step 2, modifications to observed model elements will trigger change notifications by the underlying modelling framework which are forwarded to the transformation engine (in step 3). In step 4, the transformation queries the property access trace for each change notification to determine which rule invocations are affected by the change. Finally, in step 5 the affected rule invocations are re-executed.

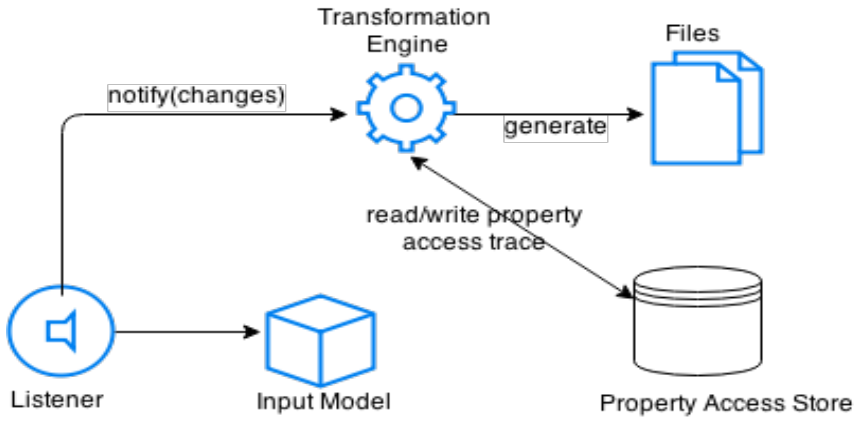


FIGURE 5.4: Overview of Online transformation using Property Access Trace.

5.5.2 Change Detection in Online Transformation.

Change detection is core to online transformation using property access traces. However not all modelling platforms provide mechanisms for observing and obtaining change notifications as changes are applied to models (e.g., a non-structured XML editor does not have a mechanism for providing change feedback). EMF provides an API which the online mode leverages to access changes as they occur in the input model. Hence, our implementation of online transformation using property access traces in EGL is based on EMF. However, before discussing details of change detection in our implementation of online transformation in EGL, we first describe the notification mechanism of EMF and types of change events that trigger change notifications.

A comprehensive list of change event types is provided in Table 5.1. Some EMF change events result from changes that are irrelevant to M2T transformations (for example, EMF produces change notifications when an adapter is removed from a model element). Our approach filters out notifications for such irrelevant events. When a feature of

a model element is modified, the modification could be state-changing or non state-changing. State-changing events alter the state of a model element while non state-changing events have no effect on the model element (e.g., adding an adapter to a model element). In case of modification of one of the ends of a bidirectional reference, change notifications are produced also for its opposite end. Of the change event types, `MOVE` and `REMOVING_ADAPTER` are the only non-state-changing event types.

Because the EMF notification mechanism observes fine-grained changes, it is highly sensitive and hence, reliable. Given the sensitive nature of the adapters, they often result in extraneous change notifications. For instance, while a change event from the perspective of a transformation developer might be perceived as a unit change (modification of a feature one model element), multiple change notifications might be triggered. For example, the creation of a new model element might be considered as a unit. However, this change operation may likely involve setting some features (e.g., name) of the newly created model element, and result in the creation of multiple notifications for what appears to be a unit change operation.

Also, while many of the change events may appear straightforward, many of them also result in extraneous change notifications, which are changes within change(s). For example, the creation of a model element may result in the following change notifications:

1. Addition of the newly created model element to a resource,
2. Insertion of a value (newly created model element) to an already existing model element e.g., adding the newly created model element to a package (or root element),
3. Setting the name (a feature) of the created model element.

Of these three change notifications, only the first and the second notifications are relevant because they may cause the transformation engine to generate new files if the transformation contains one or more rules that are applicable to the metamodel type of the created model element. On the other hand, because the third notification is for a property of a new model element that did not exist at a previous execution, it could not have contributed text to the output of a previous execution. In this case, the preprocessing intuitively does not send notifications for property changes made to newly created model elements. The number of extraneous change notifications will tend to escalate when model elements that are values in a list-based feature of another model element are deleted because such change operations will result in multiple `REMOVE` and `REMOVING_ADAPTER` change events.

Event Type	Description
ADD	Indicates insertion of a value into a list-based feature of a model element.
ADD_MANY	Indicates insertion of multiple values into a list-based feature of a model element.
MOVE	Indicates a change in the position of a value in a list-based feature of a model element.
REMOVE	Indicates the removal of a value from a list-based feature of a model element.
REMOVE_MANY	Indicates the removal of multiple values from a list-based feature of a model element.
REMOVING_ADAPTER	Indicates the removal of an adapter from a model element.
SET	Indicates a feature of a model element has been set.
UNSET	Indicates a feature of a model element has been unset.

TABLE 5.1: Table showing event types that are recognised by EMF's notification mechanism.

5.5.3 Online Transformation Execution

In our implementation of online transformation in EGL, before the initial execution of a transformation, EMF adapters are added the input model and all its model elements. An EMF adapter observes model elements to which it has been attached and provides notifications when changes occur to them. Likewise, when a new model element is created, an adapter is automatically attached to it. A change notification contains the following information: the model element whose feature was modified, and the modified feature of the model element. Each change notification is an instance of a *Change* object. There are two possibilities for handling change notifications: immediately transmit each notification as it arrives or batch the change notifications. The first approach can result in the transformation engine being inundated with irrelevant change notifications while the second approach allows preprocessing of the change notifications to remove irrelevant notifications. Our implementation follows the latter approach. This changes the transformation execution workflow described in Section 5.5.1; step 2 will entail batching change notifications before they are forwarded to the transformation engine.

However, batching change notifications in this manner introduces a concern, which is how the transformation engine determines when new sets of change notifications are available for the transformation execution to resume. In other words, transaction boundaries (Section 5.5.4) need to be defined to enable seamless transformation re-execution. A transformation session entails the initialization of a transformation, the execution of the transformation, a number of input model modifications, and the re-execution of the transformation. A transformation session ends when the transformation developer exits the transformation process.

After receiving the change notifications, the transformation engine checks the in-memory property access trace to determine which rule invocations it needs to re-execute based on the changes it has received. Since a change is structurally equivalent to a property

access, the transformation engine can determine rule invocations that are related to each change by using the property access trace.

5.5.4 Transaction Boundaries for Online Transformation.

Batching change notifications before forwarding them to the transformation engine can eliminate redundant impact analysis and change propagation activities, but determining how large batches of changes should be is challenging. There are at least two options for establishing transaction boundaries for online transformation:

1. Queue-based transaction. Change notifications can be queued when the transformation engine is executing a transformation, and change notifications may be retrieved and processed only when the transformation engine is not currently executing a transformation. However, queueing change notifications may not be sufficient, careful considerations also have to be made of change operations that reverse previous changes (e.g., undo last edit).

2. With a user-driven approach, the transaction boundary is determined by the transformation developer and the behaviour of a transformation engine is controlled by the developer. The transformation engine re-executes a transformation only when directed to do so by the user. This is a simple and pragmatic approach. It also caters for frequent change-and-undo operations because the developer can carry out any number of model modifications and re-execute the transformation when they are done with the changes.

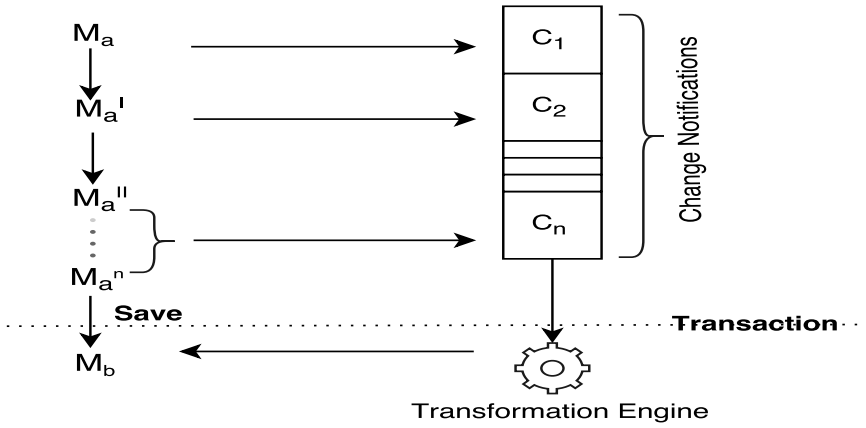


FIGURE 5.5: Overview of user-driven transaction boundary in online transformation mode.

5.5.5 Online Transformation Execution Example.

In this section, we demonstrate the way in which property access traces achieve source-incremental M2T transformation in the online mode. The demonstration is based on the same transformation example described in Section 4.4.1 and used in Section 5.5.5. Executing the transformation for the first time results in a property access trace that is equivalent to the one shown in Figure 5.6. However, it is important to note that the property access trace for *p1-trans* (Figure 5.3) now features less data, because the values of the property accesses are no longer needed to perform impact analysis.

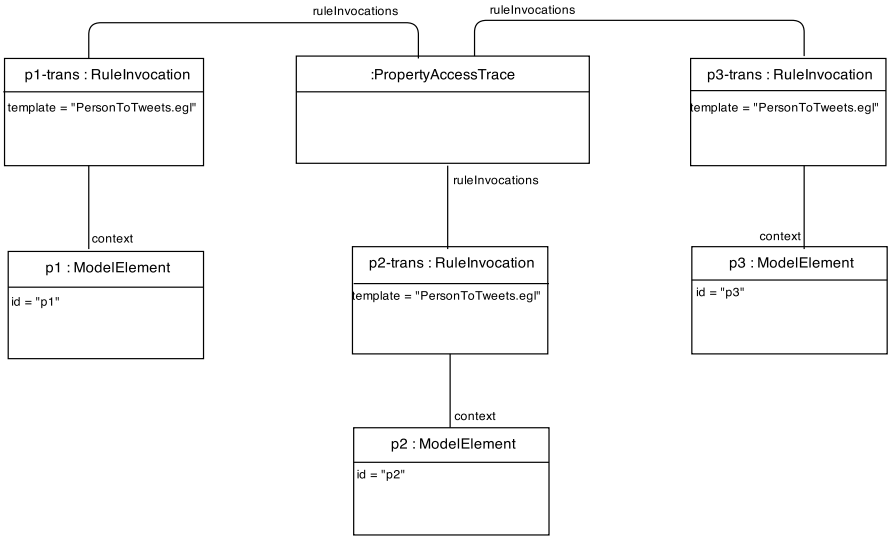


FIGURE 5.6: Online Property Access Trace generated by the invocation of rule PersonToTweets on *P1*, *P2*, and *P3*.

Executing the transformation on the simple Twitter model in Figure 4.4 causes the HTML report-generating rule to be invoked once on each person, *P1*, *P2*, and *P3*. As such, the resulting property access trace comprises three rule invocation objects (Figure 5.6). Each rule invocation object comprises several property accesses, which are recorded during the execution of the template in Listing 4.6.

Let us consider the properties accessed during the invocation of the template on *P1*. The *p1-trans* rule invocation (Figure 5.7) comprises several attribute and reference access objects and is constructed as follows. Firstly, the *p1.followers.tweets* traversal expression (line 3 of Listing 4.6) creates two property accesses: the *ra1* reference access for *p1.followers* and the *ra2* for *p2.tweets* (since *p2* is the only follower of *p1*). Since *p2* has two tweets (i.e., *T1* and *T2*), the template accesses `t1.hashTag` and `t2.hashTag` (line 5), and creates the *aa1* and *aa2* attribute accesses respectively. Finally, the *p1.tweets* expression (line 7) creates the *ra3* reference access. The boxes with a dashed border in Figure 5.7 highlight the relationship between property access objects in the

trace and the expressions in the template (Listing 4.6). Note that each property access stores a reference to the model element from which it is obtained.

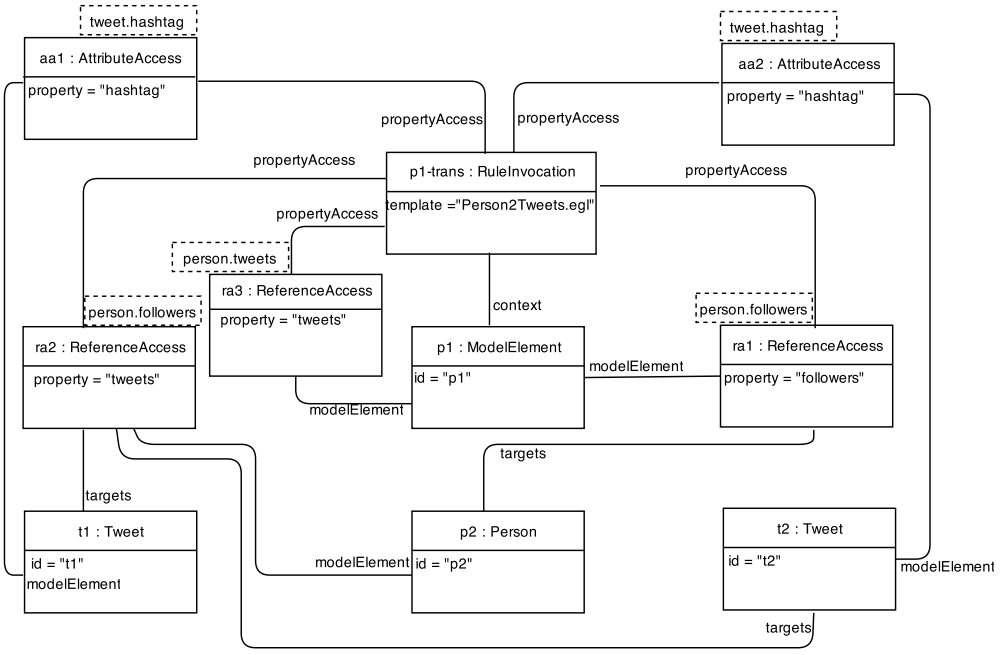


FIGURE 5.7: Property Access Trace generated by the invocation of rule PersonToTweets on *P1*.

The input model in Figure 4.4 contains three Person objects and three Tweet objects. After the initial transformation execution, the input model is modified such that two tweet objects are deleted (Figure 4.5), then the transformation is re-executed. In the online transformation mode, the transformation engine records all property accesses as they are made when a template is executed. The resulting property accesses are stored, and used during subsequent executions to determine which rule invocations will result in generation of new files, deletion of obsolete files, and/or re-generation of pre-existing files. The property access trace constructed after the initial execution of this transformation is captured in Figure 5.6. An expanded property access trace for the invocation of *p1-trans* is shown in Figure 5.7. In the online transformation mode, model changes can be batched before being forwarded to the transformation engine or each change notification may be forwarded to the transformation engine just as it occurs. For this example, we assume that change notifications are batched.

The change notifications triggered by the evolution of the input model are shown in Table 5.2. Clearly, there is a duplication of the change notification of 'tweets' feature of *P2*. This is because 'tweets' is a multi-valued feature and each time a tweet is removed from that list, a change notification is triggered. A pre-processing step removes the duplicate notification before the change notifications are sent to the transformation

engine. Therefore, only three change notifications are sent to the transformation engine for further analysis.

Model Element	Changed Feature	Event Type
P2	tweets	REMOVE
P2	tweets	REMOVE
T2	-	REMOVING_ADAPTER
T1	-	REMOVING_ADAPTER

TABLE 5.2: Change notifications triggered by the modification of the input model in Figure 4.4.

Upon receiving the change notifications, the transformation engine analyses the changes against the property access trace that was generated during the initial execution of the transformation. From Figure 5.7, the *p1-trans* rule invocation will be re-executed (based on the change notification of `REMOVE` tweets on *P2*), as will the *p2-trans* rule invocation because they are the only rule invocations that access the tweets feature of *P2*. On the other hand, the other change notifications (i.e., `REMOVING_ADAPTER` on *T1* and *T2* as a result of the deletion of *T1* and *T2* from the model) do not result in re-execution of any rule invocation. However, if there was a rule invocation that applies to the metamodel type of *T1* and *T2*, the transformation engine would have deleted any previously generated files from *T1* and *T2* because the files would have been obsolete.

5.6 Discussion

This chapter described the offline and online transformation modes, and provided detailed demonstrations of the execution of a transformation in both modes using property access traces. In this section, we highlight and discuss the differences between online and offline transformation execution using property access traces, and also discuss conditions under which property access traces cannot be applied to a M2T language for source-incrementality.

Firstly, change detection in the offline mode is conducted by the M2T transformation engine, while in the online mode, changes are detected by the tool used to edit the input model and are forwarded to the transformation engine at zero computation cost to the transformation engine. However, in the offline mode, the transformation engine has to determine the changes that have been applied to the input model by querying the input model and comparing the results of these queries with a property access trace from the last execution of the transformation. As such, in offline mode, property accesses must

contain the values of corresponding model element properties, and hence offline mode is less efficient with respect to space than online mode.

Online mode also has greater efficiency with respect to time when compared to offline mode. This is because in offline mode, the initial execution of the transformation is terminated, and resumed after a modified version of the input model is available. Recall that during a transformation execution, the transformation engine loops through all transformation rules, creates rule invocations and executes template invocations on each model element of the metamodel type specified in each transformation rule. Therefore, in offline mode, determining whether or not a template invocation needs to be re-executed requires the evaluation of *O(n)* constraints where n is the number of property accesses for that template invocation. On the other hand, in online mode, determining which rule invocations to re-execute only requires the analysis of previously recorded property accesses which is an *O(1)* operation since the transformation context is maintained in memory and the property accesses are maintained in a map of property accesses to sets of rule invocations (that accesses that property). Offline transformation scales by the size of property accesses, while online transformation scales by the size of the input model changes.

Determining which parts of the transformation to re-execute is possible because we require that transformation templates have two characteristics: they must be closed and deterministic (Section 3.2.2). A closed template takes its data only from input models, which means that the generated text is dependent only on data that we can observe. A deterministic template is one in which we can always predict which parts of the input models the template will access. Under these conditions, property accesses can be used to determine whether or not a re-invocation of a template will produce a different output after the input models have been changed. A similar correctness argument is made for the incremental model consistency checking approach in [122]. Provided that changes are limited to the input model, the templates do not contain non-deterministic constructs, and the transformation specification has not changed, then property access traces contain sufficient information to perform source-incremental transformation.

5.7 Limitations of Property Access Traces

Property access traces exhibit some limitations. Firstly, they can become over-sensitive to changes to parameters contained in unordered collections. Consider a template (e.g., `[%= Person.followers.tweets.hashtag %]`) that only prints out the 'hashtags' of a person's followers' tweets. The *PropertyAccessRecorder* records several property

accesses, including a property access of *hashtag* on each *Tweet* in the collection *Person.followers.tweets*. If in a change event, a *Tweet* is removed and re-added to the collection *Person.followers.tweets*, these modification operations will result in the same set of *Person.followers.tweets*, albeit with a different order, since the re-added *Tweet* is inserted at the end of the collection. This will cause the template to be re-executed unnecessarily. The order of collections are important for accurate comparison of modified structural features of a model element. Our current implementation does a string comparison of the values of *property accesses* recorded from calls that return a collection of structural features, and cannot detect if mere re-ordering of collections is a significant change event.

Another limitation of online transformation mode is the lack of change notifications for derived features. Derived features are features (EAttributes or EReferences) the values of which are computed from other model elements or model element features.

For example, in EMF, modification of derived features is not guaranteed to trigger change notifications. Therefore, responsibility then falls on the metamodel developer to ensure that changes to derived attributes and references produce change notifications. As a result, the performance of modelling tools that depend on EMF's change notification API is impeded by the need to specially process derived features [123].

5.8 Summary

This chapter presented *property access traces*, a novel approach which uses information derived from transformation execution for providing source incrementality in M2T languages. Evidence of the practicality of the *property access traces* technique was provided by the implementation of *property access traces* in EGL to provide source incrementality. Furthermore, in order to provide evidence of the viability of *property access traces*, a demonstration of the *property access trace* technique was provided through an incremental M2T generation of text from a model representing a social network.

In this chapter, we demonstrated how *property access traces* can be used to provide source-incrementality in scenarios which the *signatures* technique found problematic. Unlike *signatures* (Chapter 4), *property access traces* contain adequate information including model element properties that are used to determine the execution path of a template without directly contributing text to the output of the template invocation. As such, *property access traces* are sensitive to all possible model element changes that are relevant to a transformation. Through an incremental generation example, this chapter demonstrated how *property access traces* can be used to achieve source incrementality,

where the automatic signature strategy failed to generate signatures that are sensitive to changes in model elements whose features are accessed in conditional statements. Also, in contrast to the user-defined signatures, *property access traces* are fully automatic, and are not prone to human error.

Additionally, we presented another dimension to source-incrementality by showing that *property access traces* can be used in an online mode to achieve more immediate change propagation.

In addition, we highlighted the differences between online and offline transformation modes using *property access traces*. In offline mode, the transformation engine is required to detect the changed parts of an input model, but it does not have any dependency on the modelling framework. However, in the online mode, more immediate change propagation is made possible by the availability of change notifications provided by the underlying modelling framework (i.e., EMF). Thus, the online transformation mode is limited to modelling frameworks that can provide change notifications, whereas offline transformation mode has no dependency on the modelling framework for change notifications. Another difference between the offline and online transformation modes is that in online mode, the property accesses do not have to contain the values of the corresponding model element property whereas in offline mode, model element property values are essential for detecting changes.

As with the signatures technique, further evaluation of the use of *property access traces* against other requirements of a source-incremental transformation language are presented in to Chapter 6 which contains the results of empirical evaluation of the *property access traces* using real-life M2T case studies.

Chapter 6

Evaluation

Chapter 2 discussed the way in which MDE is considered to increase efficiency in software development, and how issues such as poor scalability threaten the adoption of MDE despite its benefits. Chapter 3 provided in-depth analysis of scalability in the context of M2T transformations, and also established a set of important criteria for a source-incremental M2T transformation engine.

This chapter evaluates the source-incremental techniques proposed in Chapters 4 and 5 of this thesis, with respect to the research hypothesis which states that: *contemporary approaches to M2T transformations can be extended with novel and practicable techniques which enable correct and efficient source-incremental transformations without sacrificing the expressiveness of the M2T language.* This evaluation is done in regards to scalability. As described in Section 1.5, a scalable transformation is one in which the re-execution time following a change in its input model is proportional to the impact of the change rather than to the size of the input model.

6.1 Evaluation Strategy

This section describes the methods used to evaluate the soundness, performance, and practicality of source-incremental techniques. Based on an analysis of these qualities, we determine that empirical evaluation is necessary for some parts of the evaluation. As such, we considered three case studies for the evaluation. We present and analyse these case studies in Section 6.1.4.1.

6.1.1 Evaluating the Soundness of a Source-Incremental Technique

We express the soundness of a source-incremental technique based on three attributes (i.e., source-minimality, correctness, and target-minimality) of an incremental transformation engine as outlined in Section 3.1. In this section, we describe how these attributes are assessed in the source-incremental techniques proposed in Chapter 4 (*Signatures*) and Chapter 5 (*Property Access Traces*). A possible method of evaluating the soundness of these techniques is to devise formal proofs. For example, the correctness of the algorithms can be proven by establishing a set of formal constraints on the properties of the transformation language. However, this would require defining the semantics of the host language of the M2T transformation in a formalism that supports the development of mathematical proofs (e.g., relational algebra), which is beyond the scope of this research. An alternative evaluation approach would be to extensively test the implementation of the source-incremental techniques. Ideally, this would involve a considerable number of case studies which have varying degrees of complexity and possess different characteristics in order to provide confidence in the results of the evaluation. However, it is infeasible to perform experiments on all existing M2T transformations because of time constraints and limited number of appropriate case studies. Therefore, we employ a combination of analytical arguments and testing of the implementations of signatures and property access traces via two M2T transformation case studies.

Exploring the soundness of a source-incremental transformation will seek to investigate the following questions:

Q1: Can source-incremental M2T transformations produce outputs that are indistinguishable from the outputs of equivalent non-incremental M2T transformations?

Q2: To what extent does source-incrementality enable M2T transformation engines to reduce the amount of redundant re-computations which are performed by non-incremental engines?

Q3: Can source-incrementality guarantee the removal of previously generated obsolete artefacts? As discussed later in Section 6.1.1.3, maintaining clean transformation output directories can be an important consideration for M2T transformations.

Methods for investigating each of this questions are discussed below.

6.1.1.1 Correctness

In this section, we describe methods used for evaluating the correctness of a source-incremental transformation engine and explore the part of the hypothesis which stated that *contemporary approaches to M2T transformations can be extended with novel and practicable techniques which enable correct and efficient source-incremental transformations without sacrificing the expressiveness of the M2T language.*.

The correctness of a M2T transformation can be tested by assessing whether it has produced the expected number of artefacts (not more, not less). Secondly, correctness can further be affirmed by checking the contents of the generated artefacts – the transformation is correct if it satisfies the following constraints: it does not omit expected file contents and it does not introduce data outside of the transformation specification (i.e., input model, templates, template parameters).

Generally, in software engineering testing activities, it is common for the verification process to include some form of experimentation, often with input data in order to observe the behaviour and outcome of a program under test. A common assumption of software testing is that there is an oracle - a mechanism for determining whether the output of a program is correct or not [124]. A common form of oracle is to compare some predetermined output with the actual output of a program execution. A similar approach can be applied to testing the correctness of source-incremental M2T transformation engines. Assessing the correctness of the output produced by a source-incremental transformation engine is straightforward since the same transformation can be executed by a non-incremental transformation engine, and the outputs of both engines can then be compared. If the output of a source-incremental execution of a M2T transformation differs from the output of its corresponding non-incremental execution, then, the output of the source-incremental execution is incorrect by definition. In a two-step process, the testing checks these constraints: 1. does the transformation output directory generated by the source-incremental execution contain at least all the artefacts generated by the non-incremental execution? 2. are the contents of the generated artefacts the same for both source-incremental and non-incremental executions? For the first constraint, testing must account for the fact that non-incremental transformation engines do not have the capability to remove previously generated obsolete artefacts from the transformation output directory. On the other hand, a source-incremental transformation engine removes previously generated but now obsolete artefacts. Therefore, in order to make direct comparisons of the transformation output directories of a source-incremental and non-incremental transformation engines, the transformation output directory of the non-incremental transformation must be empty before the execution of the transformation.

6.1.1.2 Source-Minimality

In Section 3.1 we established that source-minimality is a desirable attribute that a source incremental transformation engine may possess in order to efficiently support incremental re-executions of M2T transformations. Source-minimality limits the re-execution of a transformation to only a subset of template invocations whose output is affected by changes applied to input model elements. Consequently, it reduces the execution time of a transformation by eliminating redundant template executions.

Evaluating source-minimality involves determining whether an incremental transformation engine is performing any redundant re-computations as a result of re-executing template invocations which are irrelevant to the input model changes. By being source-minimal, an incremental transformation engine must re-execute only necessary template invocations. A way to assess source-minimality is to record the percentage of template re-invocations that end up producing the same content as their previous invocation.

6.1.1.3 Target-Minimality

As discussed in Section 3.1, target-minimality is the ability of the incremental transformation engine to maintain a transformation output directory that is consistent with the input model by disposing previously generated artefacts that have become obsolete following changes to the input model. In other words, the transformation output directory does not contain any generated artefact that can no longer be traced back to the input model.

In order to assess target-minimality in incremental M2T transformation engines, the output directory of the non-incremental execution of a M2T transformation can be compared with the output directory produced by the incremental execution of the same M2T transformation by a source-incremental transformation engine. After changing the input model, an M2T transformation is executed in non-incremental mode with an empty output directory. The same M2T transformation is executed by the source-incremental M2T transformation engine, however, with the same output directory maintained throughout all transformation iterations. At every transformation iteration, the contents of the output directory of the incremental execution of the M2T transformation is compared with the contents of the output directory of the non-incremental execution of the M2T transformation. The source-incremental transformation engine is target-minimal if after every pair of transformation executions, the output directories of both transformation execution modes contain the same generated artefacts.

6.1.2 Evaluating Performance and Scalability

In this section we describe how performance and scalability of a source-incremental technique with respect to runtime and space efficiency can be assessed. As stated in the research hypothesis, source-incremental execution of a transformation requires less time compared to the execution of the same transformation in non-incremental mode. Commonly, incremental model transformation approaches tend to trade-off space cost for computation time [106]. Although, space consumption is of a lesser concern due to considerable increases in recent years of the space capabilities of computing machines; nonetheless, our performance evaluation will be based on two parameters: transformation execution time and space consumption. We use this evaluation to answer the following question about runtime efficiency:

Q4: Under what circumstances are source-incremental executions of M2T transformations more time-efficient (i.e., are faster) than non-incremental M2T transformation engines?

Additionally, we describe how source-incremental techniques can be assessed for scalability. In particular, we explore whether source-incremental transformations scale by the size of the input model or by the impact of a change. This evaluation will help answer the following questions:

Q5: How much more memory and disk space cost does the source-incremental execution of M2T transformations incur than non-incremental M2T transformations?

Q6: How is the performance of a source-incremental M2T engine affected by increasing magnitude of input model changes?

Q7: How is the performance of a source-incremental M2T engine affected by increasing input model sizes?

6.1.2.1 Runtime Efficiency

Evaluating runtime efficiency aims to answer the question whether transformation execution time is always less than the transformation execution time of the same transformation using a non-incremental approach. In general, runtime efficiency depends on the size of the model changes, and the impact the changes have on the transformation, as only affected model elements and corresponding rule invocations are processed [125].

As discussed in Section 3.2.1, an effective source-incremental transformation engine expends time and resources: initially detecting changes to the input model, performing impact analysis, and change propagation. Each of these activities need to be executed in an efficient manner. However, there are important trade-offs to be considered when optimising for runtime efficiency. For instance, it is important that change detection algorithms are precise in order to ensure source-minimality, which in effect may result in a long-running change detection process. Conversely, imprecise impact analysis can cause a source-incremental transformation technique to become non source-minimal. At the same time, a precise, but computationally expensive impact analysis can degrade the performance of a source-incremental technique.

In summary, inefficient source-incremental transformation executions can become the bottleneck of the transformation, nullifying any gains in runtime efficiency. Therefore, this evaluation will be used to assess the runtime efficiency of the source-incremental techniques proposed in this thesis. An incremental execution of a transformation is expected to execute faster than a non-incremental execution of the transformation. However, considering the additional overheads (e.g., time) incurred by a source-incremental transformation engine as a result of change detection and impact analysis, during an initial execution of a transformation, a non-incremental transformation will likely execute faster than a source-incremental transformation because of the additional processing undertaken by the source-incremental engine. The initial execution of a transformation cannot be incremental, though information pertaining to the transformation which is collected during the initial execution of the transformation are crucial to subsequent incremental executions of the transformation. This suggests that if a source-incremental transformation results in the re-execution of all possible template invocations (for example, when all relevant model elements are modified), then, a non-incremental transformation will execute faster than the source-incremental transformation. This is so because the non-incremental transformation engine only performs a change propagation process (i.e., execution of template invocations) while the source-incremental engine performs change detection and impact analysis in addition. Accordingly, this evaluation will also seek to investigate the second part of the hypothesis which states that *there exists a threshold of the proportion of input model changes at which source-incremental execution ceases to be more efficient than non-incremental execution of a M2T transformation.*.

6.1.2.2 Space Efficiency

Although improved runtime efficiency is considered an important aim of incrementality, such improvements are typically achieved by a trade-off of computation cost with

space cost. For example, an incremental transformation engine that uses the signatures technique (Chapter 4) or the property access traces technique (Chapter 5) will incur space costs for persisting signature values and property access traces on disk. As such, careful consideration for space efficiency is also important, especially if the memory and disk space footprint of an incremental technique is proportional to the sizes of the input models or the subsets of the input model exercised by a M2T transformation. Space efficiency can be assessed through two parameters: memory and disk space consumption. Thus, we evaluate the space efficiency of signatures through an experiment described in Section 6.2.3 and the space efficiency of property access traces in the offline and online incremental modes through experiments in Sections 6.3.4 and 6.3.5 respectively.

6.1.3 Evaluating the Practicality of a Source-Incremental Technique

The practicality of a source-incremental technique can be explored by subjecting the source-incremental technique to pragmatic considerations. It can be assessed in two ways. Firstly, by determining whether the source-incremental technique imposes any practical limitations on M2T transformations. For example, determining whether the space requirements of the source incremental technique tend to exceed the amount of space that is available on a typical modern software development machine. Secondly, the practicality of a source-incremental technique can be assessed by determining if it generally requires additional effort on the part of a developer.

6.1.4 Case Studies

Sections 6.1.1, 6.1.2, and 6.1.3 above highlighted essential qualities that can be used to assess the effectiveness of source-incremental techniques and described how these qualities can be evaluated. Accordingly, we conduct empirical evaluations of *signatures* and *property access traces* through experiments on selected M2T case studies. This section describes the case studies that are used for empirical evaluation.

Experiments Set-up. The experiments that were performed during the evaluation work were executed on a MacBook Pro OS X Yosemite (2.5 GHz Intel Core i5, 8 GB 1600 MHz DDR3).

6.1.4.1 Selection of Case Studies

In order to evaluate the implemented source-incremental techniques, a set of M2T transformations have been selected. Based on the characteristics of the case studies, we

further analyse them in Section 6.1.4.2 to determine their suitability for investigating questions *Q1* - *Q7*. The results of these analyses are presented in Table 6.1. We define one strict requirement that each candidate M2T transformation has to fulfil and two optional requirements that may or may not be fulfilled by the candidate M2T transformations:

- **R1**: The transformation (referring to input models and transformation templates) must have existed and/or evolved independently of the techniques developed during this research. This is an *important* requirement which was set to avoid bias and provide evidence that the source-incremental techniques presented in this thesis have not been optimised for the selected case studies.

- **R2**: The transformation must be implemented in EGL/EGX. Since EGX is the only M2T language that has been extended with the proposed source-incremental techniques, it follows that the M2T transformations used for the evaluation are implemented in EGL and EGX.

  Given the popularity of Epsilon (the modelling platform on which EGL/EGX is built), it was envisaged that there would be many M2T projects implemented in EGL. However, considering that EGX is a recent extension to EGL, it was also expected that many of the publicly available EGL transformations were not implemented in EGX, and therefore require porting to an EGX implementation. As such, this requirement is two-fold: it has to be implemented in EGL (*strict*), and it can use EGX for rule-based template coordination (*optional*).

- **R3**: The transformation must contain example models (historical versions of models) which have evolved over time. This requirement is necessary in order to simulate the evolution of input models over the life cycle of a software development and avoid validity concerns that may arise as a result of bias if changes are artificially introduced into input models.

  This is an *optional* requirement because it is conceivable that existing input model versions of the M2T transformations may not be amenable to investigating questions that are related to varying the size of the input models and magnitudes of input model changes, as is required for investigation.

Three case studies were considered (and two were ultimately selected) for the evaluation described in this chapter. We analysed publicly-available M2T transformations which have a substantial number of templates, and more than one version of the input models. The three case studies identified via this method are described below:

- INESS was an EU funded project (EC FP7, grant #218575) which used M2T transformation to generate code from UML models. The aim of the INESS project was to develop an automated tool for analysing UML models (railway domain) of interlockings to determine inconsistencies between requirements and system properties that are defined by railway engineers [22]. A major component of the INESS project entailed the automatic generation of PROMELA ([20]) and mCRL2 ([21]) code from a UML input model. The transformation comprises 32 templates written in an older version of EGL (prior to the implementation of EGX as a transformation execution coordination facility). **Suitability for study:** INESS transformation satisfies requirement **R1**, does not meet **R2**, and only partially satisfies **R3** because it is implemented in a previous version of EGL. Overall, it is deemed to be a suitable case study (but needs to be ported to EGX).

- Pongo[1] is a M2T transformation, implemented in EGL, that generates data mapper layers for MongoDB, a non-relational database. Pongo consumes an Ecore model that describes the types and properties of the objects to be stored in the database, and generates Java code that can be used to interact with the database via the user-defined types and properties (without needing to use the MongoDB API). Pongo was developed by one of the supervisors of this research (Dr. Kolovos). The evaluations will use Pongo v0.5, which was released prior to our implementation of source incrementality in EGL. To replicate the effects of using a source incremental transformation engine throughout the lifetime of a development project, we used Pongo to generate Java code from the 11 versions the GmfGraph Ecore model obtained from the public Subversion repository[2] of the GMF team. GMF defines metamodels (i.e., the GmfGraph models used as input models in this experiment) for graphical, tooling, and mapping definition models. Each version of the model (GmfGraph) contains a number of changes introduced during iterations of the development of GMF. We selected GmfGraph due to the availability of historical versions, and because it was not developed at York. **Suitability for study:** Overall, it is deemed to be a suitable case study (satisfies all requirements).

- EmfCodegen [126] facilitates the generation of Java code from Ecore models. For each class in an input model, a Java interface, getters and setters methods, including factory implementations to instantiate the classes are generated. The M2T transformation of EmfCodegen is implemented in JET. It is believed that the code generation process in EmfCodegen facility, though not incremental would

[1] https://code.google.com/p/pongo/
[2] https://git.eclipse.org/c/gmf-tooling

have been well optimised due to their widespread use and popularity. For example, EmfCodegen is used in modelling tools such as Eugenia [37]. However, the M2T transformation in EmfCodegen could benefit from source-incrementality by reducing the amount of time it to re-generate graphical model editor code when input metamodels are evolved. **Suitability for study:** Not suitable, as it does not satisfy requirements *R2* and *R3*.

	Projects	
	INESS	Pongo
Templates (#)	32	5
Lines of code (#)	7093	329
Language	EGL	EGL
Model Type	UML	Ecore
Model Size	20 MB	32 Kb - 1.2 MB

TABLE 6.1: Evaluation Projects.

6.1.4.2 Analysis of Selected Case Studies

As shown in Table 6.1, the M2T case studies vary in size (i.e., in terms of the size of the transformation, number of templates, total lines of code, input model type, number of rules). Considering the number of templates and lines of code, Pongo is smaller compared to INESS. Another property of M2T transformation which has not been considered is the use of complex model queries (e.g., navigational, selection-filtering queries) in its templates. However, both selected M2T transformations make significant use of complex model queries.

	Questions						
	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Pongo	✓	✓	✓	✓	✓	✓	✓
INESS	✓	✓	✓	✓	✓	✗	✓

TABLE 6.2: Case study analysis based on Evaluation questions.

As shown in Table 6.2, considering the evaluation objectives outlined at the beginning of this chapter, both case studies can be used for investigating all of the research questions, except for Q6 which can only be investigated via Pongo (as discussed below). Using these two case studies, we have conducted three sets of experiments.

The experiments using Pongo were conducted in two phases. In the first phase, we investigate only: Q1, Q2, Q3, Q4, and Q5 using existing versions of GmfGraph models

which describes a typical model evolution that is observed in a realistic software development life cycle. In the second phase of Pongo experiments, we investigate Q6 and Q7 which specifically require manipulating input model sizes and magnitude of the changes applied to the input models. Q6 is meant to assess the behaviour of the transformation engine when the number of changes applied to the input model is increased each time the input model evolves. Similarly, Q7 assesses the behaviour of the transformation engine when the size of the input model is increased as it evolves. Hence, in phase two of the Pongo experiments, manually crafted input models with contrived changes are used.

Thereafter, in order to demonstrate that our proposed approaches scale well with complex M2T transformations, we perform an experiment with the INESS transformation which is the most complex of our case studies. Thus, INESS will be used to investigate all questions except Q6 since the input model for the INESS transformation is realistic and large. Given the size of the INESS input model, it will be challenging to introduce specific changes which the transformation will be sensitive to, as this will entail pre-determining what parts of the input model are exercised by the transformation.

6.2 Signatures

In this section we evaluate the effectiveness of using signatures (Chapter 4) in a source-incremental M2T transformation approach based on the qualities discussed in Section 6.1. The evaluation is performed on both variants of signatures: automatic and user-defined signatures.

6.2.1 Automatic Signatures

In this section we explore the effectiveness of the automatic signatures technique by investigating their soundness, performance, and practicality.

6.2.1.1 Soundness

Correctness. Evaluating the soundness of automatic signatures involves establishing that there is a subset of M2T transformations for which automatic signatures will produce the correct output, and also establishing that there is a subset of M2T transformations for which automatic signatures will not produce the correct output. In attempting to do this, we established that there is a subset of transformations for which automatic signatures cannot be relied upon to produce the correct output.

Recall that in Chapter 4, we demonstrated through contrived examples how automatic signatures can be used to extend a M2T language in order to provide source-incremental transformations as long as the transformation templates do not access model element properties that do not directly contribute text to the output of a template. Therefore, we argue that so long as this condition is fulfilled, automatic signatures are complete proxies to template invocations, and are thus sensitive to all types of changes that may alter the output of template invocations. In other words, automatic signatures can guarantee the correctness of the output of a source-incremental transformation engine whenever the aforementioned condition is satisfied.

However, given our knowledge of the limitations of automatic signatures and considering that automatic signatures are not applicable to a subset of M2T transformations (which exhibit the known limitations of automatic signatures, see Section 4.4.1), we further explore their correctness to determine if the known limitations of automatic signatures are a common feature in real-life M2T transformations. Thus, the second part of evaluating the correctness of automatic signatures involves manually inspecting the transformation templates in our case studies to determine if automatic signatures can be effectively applied to these case studies. The analysis involves assessing the composition of the case studies to determine whether automatic signatures would be applicable in real-life scenarios. In particular, we examine the templates in each case study to determine if they contain any of the known inhibiting features of automatic signatures.

Following the analyses of the templates in the Pongo transformation, no use of the inhibiting features of automatic signatures were observed. However, the templates contained in INESS transformation make several uses of model element accesses in conditional statements which only direct the execution path of the templates without contributing text to the output of the templates. A code snippet of one of these templates from the INESS transformation is shown in Listing 6.1.

The outcome of our investigation into the soundness of automatic signatures is that it is not sound in the general case. Although we have not considered other soundness attributes (i.e., source-minimality, target-minimality), without adequate guarantees of correctness, source-minimality and target-minimality are of considerable less significance. As such, in light of the results of the analysis of the INESS transformation, it is justifiable to assume that because automatic signatures are not applicable to the INESS transformation, they may also not be applicable to other real-life M2T transformations. Therefore, in the rest of this section, we do not evaluate the performance and practicality of automatic signatures. Instead, we proceed to evaluate user-defined signatures.

```
1  for (st in self.type.stateVariables) {
2    if (self.type.transitionBlocks.select(t|t.isTypeOf(SignalTransitionBlock) and
3      t.targetState.container.isDefined() and t.targetState.stateVariable = st).first.
       isDefined()) {
4      body := body + s + 'if\n';
5    }
6
7    for (tb in self.type.transitionBlocks.select(t|t.isTypeOf(SignalTransitionBlock) and
8      t.targetState.container.isDefined() and t.targetState.stateVariable = st)) {
9        trace(tb, body);
10       body := body + s + '::(msg_name == ' + tb.name + ') && ';
11       body := body + self.generateTransitionBlock(s, tb);
12       endTrace(tb, body);
13   }
14
15   if (self.type.transitionBlocks.select(t|t.isTypeOf(SignalTransitionBlock) and
16     t.targetState.container.isDefined() and t.targetState.stateVariable = st).first.
       isDefined()) {
17       body := body + s + '::else -> skip;\n';
18       body := body + s + 'fi;\n';
19   }
20 }
```

LISTING 6.1: Snippet of PROMELA2CODE_First_Template.egl taken from INESS transformation.

6.2.2 User-defined Signatures

As discussed in the previous section, a major drawback of automatic signatures is that they are insensitive to changes to model elements properties that do not directly contribute text to the output of a template. In order to address the shortcoming of automatic signatures we implemented user-defined signatures (Section 4.4.1). While automatic signatures are completely transparent to the transformation developer, user-defined signatures are derived from expressions specified by the developer. In the next section we provide analytical arguments about the soundness, performance, and practicality of user-defined signatures before discussing the results obtained from executing the Pongo M2T transformation using user-defined signatures in Section 6.2.3.

6.2.2.1 Soundness

Correctness. The correctness of the output of an incremental transformation engine that uses user-defined signatures is largely dependent on the transformation developer specifying correct signature expressions. A correct signature expression is one that evaluates to a signature value that is sensitive to all possible model element changes that may alter the output of a template execution. Based on the transformation developer's in-depth knowledge of the transformation configuration, care is taken to include all model element properties whose change are likely to result in re-execution of the template. User-defined signatures are guaranteed to produce correct output if the signature

expressions are correctly specified. Results of the experiment discussed in Section 6.2.3 support this claim.

Target-Minimality. As described in Section 2.2.2.4, the EGX transformation engine first creates rule invocations, thereafter, it executes templates on model elements of the metamodel type specified in each transformation rule. Therefore, a signature is a proxy to the execution of a template on a specific model element, such that each model element has a signature value (with respect to a template that was executed on the model element). Given the sequential execution pattern of the EGX transformation engine, a post-transformation execution analysis of the stored signatures will reveal which model elements have related signatures that were not accessed in the most recent transformation execution. Considering that all existing model elements which are relevant to the transformation will have a related stored signature, if there exists a signature whose corresponding model element no longer exists (e.g., due to deletion), then, the transformation engine can remove any files previously generated from the model element.

Towards Source-Minimality. Ideally, if signature expressions are correct, then, the transformation engine should be source-minimal because the signature values are sensitive to changes that may affect the output of their corresponding templates. However, the execution logic contained in templates may inhibit source-minimality. For example, the template in Listing 6.2, multiple execution paths can produce the same output when re-executed.

```
1
2  //scenario 1: irrelevant property access
3  [% if(aPerson.following.size() > 0) { %]
4  //do-nothing
5  [% } %]
6
7  //scenario 2: possibly the same output irrespective of change
8  [% signature = Sequence{aPerson.handle} %]
9  [% if(aPerson.handle == "Bob.Bob") { %]
10 foo
11 [% } %]
12 [% else if(aPerson.handle == "Alice.Alice") { %]
13 bar
14 [% } %]
15 [% else { %]
16 foo
17 [% } %]
```

LISTING 6.2: Example of a template that cause user-defined signatures to become non source-minimal, specified in EGL syntax

In scenario 1, any changes to *aPerson.following.size* on line 3 will result in an unnecessary re-execution of the template. However, the developer can specify a static signature

value for this template which will always evaluate to the same value each time the transformation is executed. Alternatively, they can omit *aPerson.following.size()* from the template's signature. Thus, the template is never re-executed. Scenario 2 completely breaks source-minimality because multiple execution paths of the template can result in the same output (*foo*). Despite the fact that the signature expression on line 8 is correct and sensitive to changes to *aPerson.handle*, any value of *aPerson.handle* other than *Alice.Alice* will produce *foo*. With correctly specified signature expressions and in the absence of template logic such as is demonstrated by Listing 6.2, incremental transformation engines can achieve source-minimality through user-defined signatures.

6.2.2.2 Performance and Scalability

In this section we evaluate the performance and scalability of user-defined signatures. In terms of performance, user-defined signatures cause a transformation engine to incur space costs, but we argue that this space cost does not impose any practical limitations on the transformation engine. We also evaluate the performance of transformation engines based on runtime efficiency. Finally, we evaluate the scalability of transformations performed by transformation engines that use user-defined signatures.

Space Efficiency. Persisting signature values in external storage imposes a space cost on the transformation engine. This space cost is proportional to the size of the signature values. Considering that user-defined signatures are reflections of the model element properties that are accessed during template execution, it is expected that as the number of unique model element properties increase, so do the space requirements. As we have seen in the user-defined signature expression examples in Section 4.4.1, user-defined signatures are precise, since they comprise of only model element properties accessed in templates. Moreover, user-defined signature expressions, when written according to best practice, do not contain duplicate model element properties. The preciseness of user-defined signature expressions implies that the computed signature values are concise, hence, the space requirements are expected to be minimal. We provide evidence supporting this claim based on experimental results in Section 6.2.3.

Runtime Efficiency. As discussed in Section 3.1, the overall effectiveness of an incremental transformation engine depends on whether it efficiently performs change detection and impact analysis. If change detection and impact analysis processes are excessively expensive, then, non-incremental execution of transformations may execute faster than the incremental execution. For user-defined signatures, change detection

and impact analysis are performed in the same step by re-evaluating signature expressions to determine whether the output of a template execution will be different from the output a previous execution of the same template. The re-evaluation of user-defined signatures is expected to be a less computationally expensive operation than re-executing the template because user-defined signature expressions contain fewer model element queries than their corresponding template.

Scalability. In this section we evaluate the scalability of incremental M2T transformations that make use of user-defined signatures based on the number of unique model element properties accessed in templates. The higher the number of model element properties, the more model element properties are required to compute a correct signature, thereby potentially increasing the complexity of user-defined signature expressions. The higher the complexity of user-defined signature expressions, the longer the time required to compute signature values. Therefore, the number of model element properties in a template directly affects the overall runtime efficiency of the incremental transformation engine. Apart from runtime efficiency, as discussed in the previous section, the space efficiency of user-defined signatures scales by the size of signature values (which depends on the number of model element property accesses in templates).

6.2.2.3 Practicality

An incremental transformation engine should be transparent to the transformation developer, and also guarantee confidence in the correctness of the output produced by the incremental transformation engine. Ideally, in providing support for incrementality, the transformation engine should not require developer intervention. Although user-defined signatures may be applicable to simple M2T transformations, the effort and time that will be required to maintain user-defined signature expressions will arguably increase with the complexity of M2T transformations.

In order to guarantee confidence in the correctness of the incremental transformation, user-defined signatures present an additional concern to the transformation developer. The transformation developer must first ensure that user-defined signature expressions are correct, and maintain their correctness as the transformation evolves.

In light of the above observations, user-defined signatures are applicable to M2T transformations, but they are not practical, especially when applied to complex M2T transformations. This is mainly because they can be difficult to specify and laborious to maintain when the transformation specification changes.

6.2.3 User-defined Signatures Experiment

In this section we describe the experiments conducted using user-defined signatures for the incremental execution of the Pongo M2T transformation and we discuss the results of the empirical evaluation.

Pongo Experiment: User-defined Signatures

In this experiment an empirical evaluation of user-defined signatures is conducted by executing the Pongo M2T transformation on 11 versions of GmfGraph model in both incremental and non-incremental modes. The results (Table 6.3) show the difference in number of template invocations and total execution time between non-incremental and incremental execution using user-defined signatures, for each version of the GmfGraph model.

		Non-Incremental		**User-defined Signatures**	
Version	Changes (#)	Inv. (#)	Time (s)	Inv. (#)	Time (s; %)
1.23	-	72	1.79	72	2.05 (124%)
1.24	1	73	1.72	6	1.12 (68%)
1.25	1	73	2.01	2	0.71 (43%)
1.26	1	74	2.03	6	0.65 (39%)
1.27	10	74	1.97	44	1.08 (63%)
1.28	10	74	1.95	44	1.32 (79%)
1.29	14	74	1.94	50	1.17 (69%)
1.30	24	77	2.02	72	1.38 (78%)
1.31	1	77	1.86	1	1.26 (72%)
1.32	1	77	1.95	1	0.57 (33%)
1.33	3	79	2.00	8	0.45 (24%)
			21.24		11.76 (55%)

TABLE 6.3: Results of using non-incremental and incremental generation through user-defined signatures for the Pongo M2T transformation, applied to 11 historical versions of the GmfGraph Ecore model. (Inv. refers to invocations)

Space Efficiency. With respect to memory utilization, each instance of a signature required 56 bytes of memory (on average). The maximum memory utilization observed during the Pongo experiment was 4.42 Kb during the last iteration (i.e., the execution of the transformation on version 1.33 of GmfGraph). With respect to disk space utilization, the maximum space requirement during the execution of the Pongo transformation was 80 Kb. Reduced disk space utilization can be achieved by optimizing (e.g., normalization of the signature store) the database structure.

Runtime Efficiency. As shown in Table 6.3, in the first execution of the transformation, the incremental execution mode required 24% more time than the non-incremental

mode. This is expected because in incremental mode, the transformation engine must perform an additional task while executing templates. Specifically, during the first execution of the transformation, it must evaluate signature expressions and still execute all the templates since there are no previously stored signatures. However, in subsequent re-executions of the transformation, the transformation engine limits the execution of the transformation to templates with signature values different from previously stored signature values, which results in a reduction in the execution time of the transformation. For instance, during the execution of the transformation on version 1.24 of GmfGraph, the incremental execution re-executed 6 templates compared to 73 by the non-incremental mode, and required about 68% of the execution time required by the non-incremental execution. In a project for which Pongo was applied once for each version of the GmfGraph, we observed upto 76% (see last row of Table 6.3) reduction in total execution time.

Correctness. The correctness of the output of the incremental transformation engine was assessed through the Pongo experiment. We established that the output of the incremental transformation engine on Pongo using user-defined signatures were indistinguishable from the output of the non-incremental execution of Pongo. After the execution of the transformation on each version of the GmfGraph model in both incremental and non-incremental modes, we compared the output of the incremental mode with the output of the non-incremental mode for equality. Note that each non-incremental transformation execution started with an empty directory in consideration for generated obsolete artefacts that might have been deleted by the incremental transformation engine due to target minimality.

6.2.4 Discussion

For the Pongo experiment, user-defined signatures were computed based on structural features of each model element. However, in order to avoid the painstaking process of manually writing model element features to be included in the signature expression, we used the automatic feature-based user-defined signature generation strategy described in Section 4.4.3. The implication of this is that we compromised preciseness and source-minimality. Since the feature based user-defined signature generation strategy computes signatures from all structural features of model elements, the generated signatures are overly pessimistic to changes and may lead to unnecessary template re-executions.

The alternative would be to manually write user-defined signature expressions, which is generally onerous and time-consuming. This is particularly problematic for Pongo,

```
1
2  [% for(r in c.eReferences.select(r|r.isMany)) { %]
3    [%= r.eType.getJavaName() %]
4    ...
5  [% } %]
```

LISTING 6.3: Snippet of code taken form eclass2class.egl in Pongo transformation.

where the templates have high numbers of unique model element property features, including references to other model elements. As such a user-defined signature would have required fine-grained features by identifying important features of the model elements, and the features of the referenced model elements. For instance, consider the code snippet from *eclass2class.egl* template in Pongo transformation shown in Listing 6.3. A precise user-defined signature expression must include specific model element feature accesses made on c (c is the model element on which the template is being executed), and importantly on the accesses made on the contents of $c.eReferences$ (e.g., $r.eType$).

With respect to space efficiency, during the experiment, we recorded the memory and disk space utilization of the transformation engine for processing signatures and persisting signatures in disk. We observed a peak memory utilization of 4.03 Kb while the recorded maximum disk space utilization during each execution of the transformation was about 80 Kb.

6.3 Property Access Traces

In this section we evaluate the soundness, performance, and scalability of using property access traces in both offline and online transformation modes. We first provide shared analytical arguments for the correctness, source-minimality, and practicality of property access traces, since offline and online transformation modes using property access traces are similar. Thereafter, we present separate empirical evaluations for both transformation modes, using the selected M2T case studies, and also provide further evidence backing the claims we make in our arguments about soundness, performance, and scalability.

6.3.1 Soundness

In this section, we explore the soundness of property access traces by arguing that they can be used to achieve source-minimality in incremental M2T transformation engines. The other soundness attributes (i.e., correctness and target-minimality) described in Section 6.1.1 will be assessed through experimentation via case studies.

Towards Source-Minimality. As discussed in Section 6.1.1.2, evaluating complete source-minimality is challenging for complex transformations because it is difficult to pre-determine the impact of model changes. However, for property access traces, theoretically, since a property access trace comprises only model element features that are accessed in the transformation templates (*closed templates*), and considering that re-execution of the templates will perform the same actions as in previous template invocation (*assuming determinism*, see Section 5.6), property access traces are always guaranteed to be source-minimal. Changes in the values of properties of model elements that have not been accessed in the previous transformation cycle are guaranteed not to trigger unnecessary re-execution of templates.

In addition to checking whether templates fulfil determinism and closed properties, in determining whether property access traces are source-minimal or not, we examine a property access - output mapping property of a template invocation. Given a template invocation execution such that: $P_A \leftarrow T_I \rightarrow O$, where:

- P_A is a property access
- T_I is a template invocation
- O is the output of the template invocation

In order to guarantee source-minimality, each execution of the template invocation on P_A with a distinct value must produce a distinct output. In other words, if $P_A \leftarrow T_I \rightarrow O$, and $P_A' \leftarrow T_I \rightarrow O$, then, T_I represents a template invocation that is not source-minimal since it produces the same output regardless of the changes made to a property access. Examples of such templates that exhibit non source-minimality are shown in Listing 6.4.

```
1
2  //scenario 1: irrelevant property access
3  [% if(aPerson.tweets.size() == 0) { %]
4     //do-nothing
5  [% } %]
6
7  //scenario 2: possibly the same output irrespective of change
8  [% if(aPerson.tweets.size() == 1) { %]
9    foo
10 [% } %]
11 [% else if(aPerson.tweets.size() == 2) { %]
12   bar
13 [% } %]
14 [% else { %]
15   foo
16 [% } %]
```

LISTING 6.4: Example of a non source-minimal template specified in EGL syntax

In scenario 1 of Listing 6.4, the template invocation accesses a model element's feature (line 3) but does not use its value in the generated text. In this example, the property access trace generated from executing this template causes the transformation engine to be overly pessimistic because whenever the number of tweets of *aPerson* changes, the transformation engine determines it needs to re-execute the template based on the property access trace and the new value of *aPerson.tweets.size()*. Likewise, in scenario 2 of the same Listing (6.4), any change that causes the size of a *aPerson*'s tweets to be any number other than two, produces the same output (*foo*) due to the closing *else* block (line 14).

In such scenarios, a property access trace can result in an unnecessary re-execution of the template when the template code is structured such that blocks of code which access model element property do not alter the output of a template irrespective of whether the value of a property access is modified.

In summary, provided transformation templates are closed, deterministic, and devoid of the type of code structure described above, property access traces can be used to eliminate redundant re-computations.

6.3.2 Performance and Scalability

In this section, we first assess the performance of property access traces with respect to space and runtime efficiency. Then, we assess the scalability of the offline and online transformation modes along three dimensions: model size, number of property accesses, and the magnitude of input model changes. We conclude each discussion with comparisons of offline and online incremental executions of the selected transformations.

Space Efficiency. Property access traces impose space costs that are proportional to the number of unique model element features accessed by the transformation. In principle, the sizes of property access traces do not impose a practical limitation, because recorded property access traces are only a fraction of the actual input model. However, we carefully considered the factors that may affect the sizes and memory footprint of the persisted traces. Since property accesses are recorded from template invocation executions, the size of recorded traces will vary by transformation and depend on factors such as the average number of property accesses per template, the proportion of dynamic to static sections in templates, model size, repeated property accesses.

Arguably, the higher the number of property accesses in a transformation's templates, the larger the property access trace. The number of property accesses in templates

could also be a reflection of the ratio of dynamic to static sections in the templates. For example, since property accesses are recorded from the execution of model query expressions in dynamic sections of templates, higher dynamic to static ratios could be an indication of more property accesses. However, as discussed in Section 5.4, considering that templates can contain duplicate accesses to model element features, only unique property accesses are stored in order to minimise space requirements. Another related factor is the size of the input model. In principle, the size of a property access trace is not necessarily related to the size of the input model, but in practice it often is (as we will highlight in our experimental results in Section 6.3.6). It can be assumed that the larger the input model, the more model elements and model element features are accessed by a transformation, and hence, the larger the space that will be required to store and process property access traces.

In light of the above, the actual effect of the average number of property accesses per template, the proportion of dynamic to static sections in templates, model size, repeated property access on the space costs of property access traces depends on the nature of the transformation. We discuss the results of the experiments conducted with our case studies in relation to space costs in Section 6.4 by focusing on actual memory and physical disk costs incurred during the execution of the case studies.

In concluding space efficiency evaluation, we compare the offline and online transformation modes. Recall from Chapter 5 that in offline transformation mode, a property access comprises the id of a model element, name of an accessed feature, and the value of the accessed feature. In contrast, in online transformation mode, a property access includes only the id of a model element, and the name of an accessed property (but not the value). Therefore, the space cost incurred during online transformation is less than during offline transformation.

Runtime Efficiency. An important consideration in evaluating the runtime efficiency of property access traces is the complexity of the incremental algorithm. An analysis of the incremental algorithm will provide insights into the runtime performance and scalability of the technique. In analysing the complexity of property access traces, we also need to consider the way in which the transformation engine that employs property access traces executes a transformation, and whether a transformation is executed in online or offline mode. Therefore, we briefly recap the transformation execution process of EGX.

As described in Section 2.2.2.4, during the execution of an EGX transformation, the transformation engine creates a rule invocation for every rule specified in the transformation specification. Then, for each rule invocation, it creates template invocations for

every model element of the correct metamodel type (as specified in the transformation rule) by traversing the input model.

In the offline mode, the transformation engine must detect model changes and perform impact analysis by inspecting the previously stored property access trace, and querying the input model to determine whether the value of each model element feature of interest has been changed. Therefore, in the offline mode, determining whether or not a template invocation needs to be re-executed requires the evaluation of *O(n)* constraints where n is the number of property accesses for that template invocation, and it also requires a full traversal of the input model[3]. This implies that in the offline mode, the transformation scales according to the proportion of the input model that is exercised by the transformation and the size of the property access trace. On the other hand, because in the online mode, the transformation engine does not need to detect model changes, and the in-memory representation of property access trace is a map of property accesses to sets of rule invocations (that accesses that property), performing impact analysis only entails looking up a property access in the map which is an *O(1)* operation (the map is keyed by a combination of model element id and an accessed feature name). Online transformation using property access traces scales by the impact of the input model changes. Later in Section 6.3.4 we discuss the effect of this on the runtime efficiency of property access traces using experiments based on our case studies.

Scalability. We assess the scalability of M2T transformations using property access traces based on three factors: input model size, number of property access traces, and the magnitude of input model changes. As discussed in the previous section, the extent to which the input model size affects the runtime and space requirements of an incremental engine using property access traces depends on the proportion of the input model that is exercised by the transformation. For example, consider two M2T transformations, the first of which consumes a large input model, but only accesses a small subset of it (e.g., 1%). On the other hand, the second transformation consumes a much smaller input model but accesses it in its entirety. We will argue that the transformation engine, due to the second M2T transformation having fully exercised the its input model will incur more space cost than the space cost requirements for the first M2T transformation. Based on this argument, M2T transformations that use property access traces scale by the effective input model (proportion of the input model that is relevant to the transformation) size, and not by the size of the input model.

[3]Ideally, a full model traversal is unnecessary because the previously stored property access trace contains information about model elements and properties that the transformation exercises. However, a full traversal is required because the input model has to be loaded into memory, and current modelling frameworks do not support arbitrary access.

So far, we have considered two factors which contribute to the scalability of M2T transformations in terms of space efficiency. The number of input model changes only affects the runtime efficiency of the M2T transformations because it represents the impact that the changes can have on the transformation. In general, the larger the number of input model changes, the higher the impact of the changes (i.e., the more template re-executions required). Also, in general, the lower the number of template executions, the lower the transformation re-execution time. As such, in general, M2T transformations using property access traces scale by the impact of the input model changes.

Empirical evidence in support of the claims made above is presented in Section 6.3.6 where we perform experiments with the INESS transformation.

6.3.3 Practicality

Property access traces rely on recording specific model element feature accesses in-between executions to enable source-incrementality. In general, property access traces are practical because they do not require human intervention. This is evident in our application of property access traces to real-life M2T transformation experiments in Sections 6.3.4 and 6.3.5.

However, it is important to note that in the online transformation mode, the transformation engine is reliant on receiving change notifications from the underlying modelling framework (e.g., EMF). Therefore, in the absence of change notifications, online transformation is infeasible.

6.3.4 Offline Transformation Experiments

In this section we describe the experiments conducted using property access traces in the offline transformation mode and discuss the results of the empirical evaluation.

The results of the experiments presented in this section are twofold. Firstly, we evaluate the soundness of property access traces by applying the technique to Pongo M2T in the offline transformation mode. The first part (Pongo Experiment I) will investigate property access traces in relation to questions *Q1* - *Q4*. In the second part (Pongo Experiment II, in Section 6.3.4) of the experiments, we investigate the degree to which the performance of a source-incremental transformation engine is affected by increasing the magnitude of input model changes (*Q6*).

Pongo Experiment I: Offline Transformation

In this experiment an empirical evaluation of offline incremental transformation is conducted by executing the Pongo M2T transformation on 11 versions of GmfGraph model in both incremental and non-incremental modes. The results (Table 6.4) show the difference in the number of template invocations and total execution time between non-incremental and source-incremental execution using property access traces in the offline mode, for each version of the GmfGraph model.

		Non-Incremental		**Incremental**	
Version	Elements Changed (#)	Invocations (#)	Time (s)	Invocations (#)	Time (s; %)
1.23	-	72	1.79	72	2.29 (128%)
1.24	1	73	1.72	6	0.49 (28%)
1.25	1	73	2.01	2	0.50 (25%)
1.26	1	74	2.03	6	0.53 (26%)
1.27	10	74	1.97	44	0.95 (48%)
1.28	10	74	1.95	44	0.93 (48%)
1.29	14	74	1.94	14	0.56 (29%)
1.30	24	77	2.02	38	0.94 (47%)
1.31	1	77	1.86	0	0.49 (26%)
1.32	1	77	1.95	0	0.48 (25%)
1.33	3	79	2.00	8	0.57 (29%)
			21.24		8.73 (41%)

TABLE 6.4: Results of using non-incremental and offline property access traces for incremental M2T transformation for the Pongo M2T transformation, applied to 11 historical versions of the GmfGraph Ecore model.

Runtime Efficiency. For the first invocation of the transformation (version 1.23), the source-incremental mode of execution took 28% longer to execute than the non-incremental mode because the former incurs an overhead as it must record property accesses for every template invocation and store the property access trace for the transformation. In every subsequent invocation of the transformation, the incremental mode of execution required between 25% and 48% of the execution time required by the non-incremental mode. In a project for which Pongo was applied once for each version of the GMF project, we observed a reduction of up to 75% in total execution time (see highlighted row in Table 6.4). The overall reduction in execution time (12.51s) is modest, but this is partly explained by the relatively small size of the Pongo transformation (6 EGL templates totalling 329 lines of code), and of the GmfGraph model (averaging 65 classes).

Target-Minimality. The evolution of the input model (i.e., GmfGraph) from version 1.29 to 1.30 included the deletion of a model element on which a template invocation had previously been executed. In other words, the model element deletion is of relevance to the transformation. Given the presence of model element deletions in the evolution cycle of GmfGraph model, Pongo M2T is a suitable project for assessing

the target-minimality criterion. During the execution of the transformation on version 1.29 of the input model, *FigureMarker.java* and *FigureHandle.java* files were generated from *FigureMarker* and *FigureHandle* classes respectively following the execution of rule *EClass2Class* on *FigureMarker* and *FigureHandle*. In the following iteration, the deletion of both *FigureMarker* and *FigureHandle* from the input model caused the transformation engine to remove both *FigureMarker.java* and *FigureHandle.java* files from the transformation output directory. The ability of the transformation engine to detect a deletion requiring the removal of obsolete files is possible because the stored property access trace contains enough information about each model element and corresponding template invocations. Moreover, the transformation engine performs a full model traversal during each transformation execution. Using the stored property access trace, it is able to identify model elements it accessed during a previous transformation execution which are not part of the evolved version of the input model.

Correctness. During each iteration, after the execution of the transformation (i.e., in non-incremental and incremental modes), the outputs of the transformations were compared for equality. Considering that the non-incremental transformation is unable to remove obsolete files from the transformation output directory, each non-incremental execution started with an empty output directory. As described in Section 6.1.1.1 the output of the non-incremental transformation execution is the oracle for testing the correctness of the source-incremental transformation execution. Therefore, an unpolluted transformation destination directory of the non-incremental execution is required to perform accurate comparison of the transformation (non-incremental and source-incremental) outputs. Expectedly, since Pongo M2T templates are *closed* and *deterministic*, the results obtained from this experiment indicate that the output produced by using property access traces were consistent with the output of the non-incremental execution.

Pongo Experiment II: Offline Transformation

In order to explore the second part of the hypothesis which states that: *there exists a threshold of the proportion of model changes at which source-incremental execution ceases to be more efficient than non-incremental execution of a M2T transformation.*, we attempt to answer question Q6 through a second experiment involving the Pongo transformation.

Note that this experiment differs slightly to the first Pongo experiment in Section 6.3.4. There, we applied the transformation to GmfGraph models. Here, we applied Pongo to synthetic Ecore models. Recall that a major requirement of Q6 is that the magnitude

of changes made to the input model is varied, therefore, we needed to orchestrate the evolution of the input model. Also, recall that the GmfGraph models are different versions that evolved naturally. As such, we created an input model which we manipulated over several iterations to investigate whether property access traces continue to be effective as the proportion of change in the input model increases. In particular, we sought to identify how large a change to the input model would have to be in order for incremental transformation to become slower than non-incremental transformation due to the overhead incurred in querying its property access trace.

The input models were constructed via a script that generated classes with identical structure (a constant number of attributes and no associations). The models comprised 1000 classes, and each class had 3 attributes (see Appendix B). We executed Pongo on the model, made changes to the model, and re-executed Pongo in incremental offline and non-incremental modes. At every iteration, we varied the proportion of change made to the model. We changed the model by modifying a subset of all classes (by renaming each class in that subset and one of its attributes). We chose this type of modification because, as developers of the input model, we knew that the transformation would be sensitive to these changes. Moreover, since there are no inter-dependencies between the input model classes, we knew that there was only one-to-one mapping of model elements and files generated from each model element. In other words, we selected this type of modification to avoid changing the model in a way that had a very small or a very large impact on the generated artefacts.

	Non-Incremental		**Incremental**	
Changes (Elements #; %)	Templ. Invocations (#)	Time (s)	Templ. Invocations (#; %)	Time (s)
-	1000	5.10	1000	6.20
1 (0.1%)	1000	4.97	1 (0.10%)	2.32
10 (1%)	1000	5.79	10 (1.00%)	2.35
20 (2%)	1000	4.77	20 (2.00%)	2.31
100 (10%)	1000	5.62	100 (10.00%)	2.48
300 (30%)	1000	5.53	300 (30.00%)	3.21
600 (60%)	1000	4.94	600 (60.00%)	5.64
700 (70%)	1000	5.01	700 (70.00%)	5.73
800 (80%)	1000	4.98	800 (80.00%)	6.52

TABLE 6.5: Results of using non-incremental and incremental offline M2T transformation for the Pongo M2T transformation, applied to increasingly larger proportions of changes to the source model.

As shown in Table 6.5, our results suggest that source incremental transformation using *property access traces* requires less computation until a significant proportion (threshold) of the input model is changed. In this case, that threshold was reached when approximately 60% of the input model was changed (see the highlighted row in Table 6.5). This corresponds to 1200 changes, as 2 changes were applied to each changed model element. The threshold will be different for other transformations, and will depend on factors such as the amount of *property accesses* in templates, and the complexity of model queries in the templates.

For property access traces, incremental offline transformation provides the base performance of the technique. We envisaged that the threshold at which non-incremental transformation engine will out-perform an incremental transformation engine for this experiment on Pongo will be higher than 60% in the online transformation mode. To test this assumption, we performed the same experiment in the online transformation mode, and observed that for the Pongo transformation, the incremental transformation engine out-performed the non-incremental transformation engine until about 90% of the input model was changed. (see Appendix A for full results). The difference in threshold points for incremental offline and online transformations using property access traces is expected given that in the online transformation mode, the transformation engine does not compute model changes.

6.3.5 Online Transformation Experiments

As discussed in Section 5.6, online incremental transformation using property access traces is fundamentally similar to the offline variant. Accordingly, the discussions on analytical evaluation of the soundness, performance, and practicality of property access traces addressed both offline and online transformation modes. Therefore, in this section, we only present empirical evaluation specific to incremental online transformation.

Pongo Experiment III: Online Transformation

The evolution of GmfGraph represents various re-structuring and re-factoring steps that normally occur during a development project. As already discussed in Section 6.1.4.1, GmfGraph was chosen as the input model for the Pongo M2T transformation experiments because it has evolved independently of the source-incremental techniques proposed in this thesis. The existence of naturally existing changes removes a potential source of bias from our evaluation. Moreover, it allows us to investigate source-incremental M2T in a realistic context.

Performing experiments on online transformation using property access traces requires that the input model is modified concurrently as the execution of the transformation. Therefore, experiments that simulate real life evolution of an input model present a challenge: reverse engineering the input model to derive changes applied to an older version of the input model at each evolution iteration. In GmfGraph, for example, reverse engineering the input models will enable the extraction of changes in-between two versions (a newer version and the version immediately preceding it) of the input model. This is followed by the application of the derived changes to older version of

the input model during transformation execution, in order to observe the behaviour of the transformation engine during online transformation.

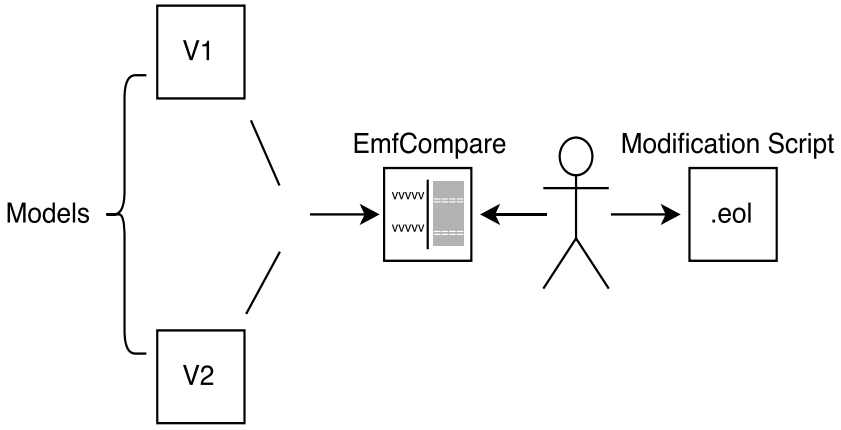


FIGURE 6.1: Overview of Re-constructing GmfGraph model Evolution.

To evaluate property access traces in online transformation mode using Pongo M2T, we first had to re-construct the changes that existed in-between the 11 versions of GmfGraph. This is a manual process which is depicted in Figure 6.1. In the first step, we determined the differences between an input model and its preceding version. This was done using the EmfCompare([127]) tool which computes a *difference* model by comparing two models. EmfCompare has a graphical user interface which shows the differences between two models in both textual and tree view formats. In the next step, we manually encoded the changes identified via model differencing as an EOL script that could be used to evolve model from its current version to the next version.

Considering that our experiment replays the evolution of the input models, it is important to note that during this process, the changes between the versions of the input model are batched before being forwarded to the transformation engine (as depicted in Figure 6.2). As described in Section 5.5.4, we simulate an event-driven transaction boundary whereby change notifications are forwarded to the transformation engine only after the developer saves the model. This is based on the assumption that during the evolution of each version of the input model, the changes were applied in a single modification session because this information is not stored in either version of the model. Moreover, it is impossible to determine exactly what changes were done and undone during the real evolution of the input model.

Another important observation was that because the EMF change notification mechanism is fine-grained, change notifications were being triggered for every create, set, update, and delete statement in the EOL scripts. Many of these change notifications were however extraneous. For instance, the evolution of version 1.24 to 1.25 is captured in Listing 6.5. Despite the fact that there exists only a single change between version

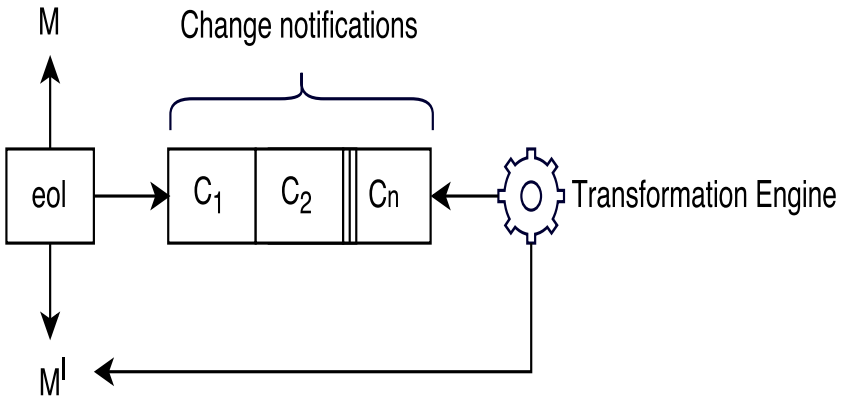


FIGURE 6.2: Overview of online execution of Pongo on GmfGraph.

1.24 and 1.25 (one additional element), the modification script contains five modification (creating, setting attributes and references values) operation statements (lines 4 - 10), triggering five change notifications. However, following an analysis of the change notifications, only two change notifications are relevant to the transformation. The relevant change notifications are the creation of an EAttribute (i.e., affixedParentSide) and the modification of the eStructuralFeatures of *Node* (line 10). As a modification script is executed on an original version of the input model, change notifications are sent to the transformation engine, and the transformation is re-executed.

```
1  var node = gmfgraph!EClass.all.selectOne(dt | dt.name == "Node");
2  var direction = gmfgraph!EEnum.all.selectOne(dt | dt.name == "Direction");
3
4  var affixAttr = new gmfgraph!EAttribute;
5
6  //modifications
7  affixAttr.name = "affixedParentSide";
8  affixAttr.setEType(direction);
9  affixAttr.setDefaultValueLiteral("NONE");
10 node.eStructuralFeatures.add(affixAttr);
```

LISTING 6.5: EOL script containing change operations executed on v1.24 of GmfGraph model which produces v1.25.

The results of the Pongo M2T transformation using property access traces in the online transformation mode are presented in Table 6.6. Expectedly, the total execution time of the transformation in online transformation mode is less than the total execution time observed for the non-incremental execution of the transformation. The online transformation mode required about 25% of the total execution time of the non-incremental transformation. Likewise, the total number of template invocations in the online transformation mode is about 28% of the total template invocations executed during the non-incremental transformation.

		Non-Incremental		Incremental	
Version	Elements Changed (#)	Invocations (#)	Time (s)	Invocations (#)	Time (s; %)
1.23	-	72	1.79	72	2.42 (135%)
1.24	1	73	1.72	6	0.14 (8%)
1.25	1	73	2.01	2	0.06 (3%)
1.26	1	74	2.03	6	0.13 (6%)
1.27	10	74	1.97	44	0.65 (33%)
1.28	10	74	1.95	44	0.63 (32%)
1.29	14	74	1.94	14	0.20 (10%)
1.30	24	77	2.02	38	0.79 (39%)
1.31	1	77	1.86	0	0.03 (1%)
1.32	1	77	1.95	0	0.02 (1%)
1.33	3	79	2.00	8	0.24 (12%)
		824	21.24	234 (28%)	5.31 (25%)

TABLE 6.6: Results of using non-incremental and property access traces for online incremental M2T transformation for the Pongo M2T transformation, applied to 11 historical versions of the GmfGraph Ecore model.

Although as shown in Figure 6.3, a similar pattern of execution times is observed for the execution of the transformation in both online and offline modes, the online execution required less time compared to the offline execution. The difference in execution time is due to the fact that the transformation engine in the online mode does not need to compute model changes. Furthermore, in the online mode, the transformation engine does not have to query the input model to determine whether the value of a model element property has changed, hence, it can perform impact analysis quicker than in offline mode. Expectedly, since in the online transformation mode, the transformation engine receives change notifications from the model editor, change detection is achieved at no computation cost to the transformation engine. Additionally, in offline mode the transformation engine performs a full traversal of the input model and analyzes an entire stored property access trace in order to determine template invocations that require re-execution. In other words, offline mode requires the evaluation of *O(n)* constraints where n is the number of property access traces. On the other hand, during impact analysis in the online mode, the transformation engine only analyzes the stored property access traces, which is an *O(1)* operation. This is shown clearly in the highlighted rows in Table 6.7 when during the evolution of the model from version 1.30 to 1.31, and 1.31 to 1.32, which comprised single changes to the input models, the transformation engine in offline mode still took approximately 0.5 seconds despite the fact that the changes were irrelevant to the transformation (i.e., did not result in the re-execution of any template invocation). On the other hand, the online mode took significantly less time (about 0.02 seconds).

		Non-Incremental		Incremental (Offline)		online	
Version	Changes (#)	Inv. (#)	Time (s)	Inv. (#)	Time (s; %)	Inv. (#)	Time (s; %)
1.23	-	72	1.79	72	2.29 (128%)	72	2.42 (135%)
1.24	1	73	1.72	6	0.49 (28%)	6	0.14 (8%)
1.25	1	73	2.01	2	0.50 (25%)	2	0.06 (3%)
1.26	1	74	2.03	6	0.53 (26%)	6	0.13 (6%)
1.27	10	74	1.97	44	0.95 (48%)	44	0.65 (33%)
1.28	10	74	1.95	44	0.93 (48%)	44	0.63 (32%)
1.29	14	74	1.94	14	0.56 (29%)	14	0.20 (10%)
1.30	24	77	2.02	38	0.94 (47%)	38	0.79 (39%)
1.31	1	77	1.86	0	0.49 (26%)	0	0.03 (1%)
1.32	1	77	1.95	0	0.48 (25%)	0	0.02 (1%)
1.33	3	79	2.00	8	0.57 (29%)	8	0.24 (12%)
			21.24		8.73 (41%)		5.31 (25%)

TABLE 6.7: Comparison of a non-incremental, incremental transformation using property access traces in offline and online modes for the Pongo M2T transformation, applied to 11 historical versions of the GmfGraph Ecore model. (Inv. refers to invocations)

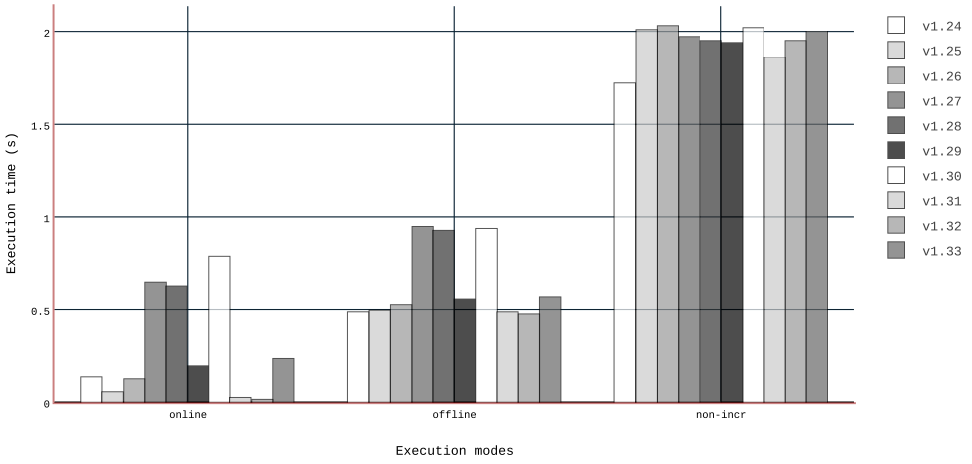


FIGURE 6.3: Comparison of Pongo M2T execution in online, offline, non-incremental modes on 11 versions of GmfGraph model.

6.3.6 INESS Experiment

Having explored the research hypothesis in the previous sections by investigating questions Q1 - Q7, we use the INESS experiment as further supporting evidence that property access traces are amenable to complex incremental transformations. In order to demonstrate that property access traces scale well with complex M2T transformations, we perform an experiment with the INESS transformation which is the most complex of our case studies. Note that we do not consider user-defined signatures for this experiment because of the amount of time and effort it would require to manually analyse and specify correct signature expressions, and the practical limitations of signatures discussed in Sections 4.4.1 and 4.4.1.

It is important to note that for this experiment, only one version of the input model is available. This is because the INESS project team did not manage artefacts of the project through a version control system. Nonetheless, the INESS transformation is suitable for investigating questions Q1 - Q5, and in particular Q7. Recall that so far, our experiments have involved M2T transformations with relatively smaller input models compared to the input model of INESS transformation. Therefore, we use the INESS transformation to assess whether property access traces can cope with large input models such as that consumed by the INESS transformation.

As discussed in Section 1.3.1, the INESS M2T transformation did not lend itself to efficient propagation of input model changes to the generated artefacts. A subset of the transformation which was responsible for the generation of mCRL2 code required about 7 hours to re-execute, even when only a single change is applied to the input model. This is because the EGL transformation engine (at that time) did not support source-incremental M2T transformations.

For our experiment, we only consider the subset of INESS M2T transformation that generated mCRL2 code because it represents a bottleneck of the transformation. It is also a complex part of the transformation: the input model from which mCRL2 code was generated was about 20 MB and contained about 119 621 model elements. Additionally, the transformation comprised 6 templates, 2 of which do not generate any text.

During the first iteration, we executed the transformation in incremental and non-incremental modes. In subsequent iterations, we methodically introduce changes into the input model before re-executing the transformation in both non-incremental and incremental modes. The input model comprised of two major parts that are accessed by the transformation templates. The first part contained Route, Signals, TimeEvent, and DataType definition classes. The second part contained ProcessType and ProcessRoute class objects. Since the input model is made up of two main parts, in the second iteration, we modify a particular subset of the input model (i.e., the part containing ProcessType objects) by randomly selecting a ProcessType model element. In the third iteration, we randomly selected and modified an element from the second part of the input model (i.e., an ObjectProcess element), in addition to modifying a randomly selected ProcessType object as was done in the second iteration. In the fourth iteration, we applied an additional change to an ObjectProcess element. Finally, during the fifth iteration, we combined modifications from the second through the fourth iterations with the modification of a randomly selected Signal object from the second part of the input model. Hence, the final iteration comprised changes that apply to both parts of the input model. Since the domain of the INESS transformation is out of our

expertise, the modification strategy was determined via exploration. This modification strategy ensured that we only modify parts of the input model that are relevant to the transformation. We assumed that the modifications simulate the kind of changes that the original project team would have carried out. All the model element modifications were straightforward updates of a property of the model elements (e.g., changing the name of an ObjectProcess element). We describe the results of the experiment in relation to Q7 below.

		Non-Incremental		**Incremental**	
Iteration	Elements Changed (#)	Invocations (#)	Time (s)	Invocations (#)	Time (s; %)
1	-	4	25 072	4	50 218 (200%)
2	1	4	25 511	1	5.23 (0.02%)
3	2	4	24 122	2	10.77 (0.04%)
4	3	4	24 901	3	11.10 (0.04%)
5	4	4	25 227	4	51 017 (202%)

TABLE 6.8: Results of using property access traces for offline incremental M2T transformation of INESS M2T transformation compared to the non-incremental execution of the transformation.

The results shown in Table 6.8 provide further evidence that property access traces can be used to reduce the amount of time required to propagate model changes to generated artefacts. Apart from this, the results also provide interesting insight into the nature of the INESS transformation; the amount of time required to re-execute the transformation in incremental mode during iteration 5 is 200% of the time expended re-executing the transformation during iteration 4. Considering that only one additional file is re-generated during iteration 5 compared to iteration 4, there is a disparity in the re-execution time observed during iterations 4 and 5. This disparity is due to the fact that the INESS transformation includes a long-running, monolithic template (mCRL2_procs_v2.egl) from which a large file was generated. The re-execution of the *mCRL2_procs_v2.egl* template accounted for more than 99% of the total execution time of the transformation. Precisely, it required about 14 hours to execute in incremental mode, and generated a file that is about 25 MB on disk.

As the main purpose of the INESS M2T experiment was to demonstrate that property access traces are tractable with respect to space and memory usage for M2T transformations of high complexity (e.g., transformations that consume large input models), we describe our observations during the experiment in terms of memory and disk space utilization. As summarized in Table 6.9, a total of 88,011 unique property accesses due to access operations made on 32,117 model elements, were recorded during the execution of the transformation. This figure indicates that about 27% of the input model elements are accessed while about 73% (proportion of model element features) of the input model is not accessed by the transformation. Note that this figure remained unchanged throughout the five iterations because the input model modifications did not

include deletions of model elements. The average memory utilization recorded during the execution of INESS M2T was 4.22 MB. The property access trace was persisted in a database file which occupied about 19.7 MB of disk space.

Input model			**Property Access Trace**			
Size (MB)	Elements (#)	Features (#)	Size (MB)	Elements (#)	PA (#)	Memory (MB)
20	119 621	481 147	19.7	32 117 (27%)	88 011 (18%)	4.22

TABLE 6.9: Summary of the space requirements for the INESS transformation.

In conclusion, based on the results of the INESS M2T experiment and our observations of the space required for this experiment, there is evidence that the performance of a source-incremental M2T transformation engine using property access traces is not related to the size of the input model, but instead, it depends on the size of the exercised part of the model. As we have seen from the INESS M2T experiment, the property access trace generated from an input model of 20 MB required about 19.7 MB to be persisted on disk and 4.22 MB to be processed in memory. These space utilization figures are considered reasonable compromises for increased runtime efficiency given that modern software development machine commonly have hundreds of gigabytes of disk space and several gigabytes of RAM.

6.4 Discussion

Our experiments suggested that property access traces and signatures improve the scalability of M2T transformations. From our results, the time required to incrementally propagate changes from input models to generated artefacts depended on the impact of the changes made to the models. For instance, in the Pongo experiment (Section 6.3.4), the incremental execution of the transformation did not cease to be more efficient than the non-incremental execution until about 60% of the templates required re-execution. As such, small changes can be efficiently propagated across generated artefacts without re-executing the transformation in its entirety. However, achieving source-incrementality comes with trading additional memory costs for computation costs. This is a common compromise in incremental computation techniques in software engineering. In general, the memory requirements of a property access trace depends on the number of property accesses contained in the trace. For instance, in the Pongo M2T experiments on GmfGraph models (Section 6.3.4), the average number of property accesses was 797 which represents about 38 kB in memory cost. In contrast, the average number of property accesses for the same Pongo transformation executed on the synthetic Person model (Section 6.3.4) was 9998, with a memory consumption of 470 kB. This difference in memory requirements of the same transformation when

executed on different sets of input models supports our argument in Section 6.3.2 that property access traces scale by the number of property accesses. Furthermore, the disk space required to persist a property access trace depends on the number of property accesses contained in the trace. However, property access traces generated in online transformation mode require less disk space compared to property access trace generated in offline mode. This is because, in the online transformation mode, a property access does not include the value of the property access, and so occupies less space on disk. For instance, the average disk space consumption of the execution of Pongo M2T on GmfGraph models in the online mode was 236 kB, in contrast to 252 kB in offline mode. Similarly, the execution of Pongo M2T on the Person model in the online mode required 2.1 MB of disk space, in contrast to 2.4 MB in the offline mode.

The scalability benefits of property access traces and signatures can be explained by considering their approach to change detection. With respect to change detection, both signatures and property access traces (in offline transformation mode) employ similar strategies. Change detection is performed at runtime through a computationally less expensive operation compared to techniques such as model differencing which require loading two versions of an input model, and at least three full model traversals. For example, Xpand's source-incremental M2T transformation engine uses model differencing to detect input model changes. However, the efficiency of such incremental transformation engine is heavily dependent on the effectiveness and the efficiency of the underlying modelling framework to compute model differences. For instance, computing model diffs for all the versions of GmfGraph models used for the Pongo M2T transformation took about 1.3 seconds (average) using EmfCompare which is the same tool that Xpand uses to compute model diffs. This figure which represents the time taken to perform only a part of the computation done by Xpand's incremental transformation engine exceeds the *total* time taken to execute each Pongo transformation on all versions of the same GmfGraph models (see Table 6.7).

Finally, we compare online property access traces, offline property access traces, and signatures. We make recommendations about the suitability of each technique given different conditions. Online and offline property access traces differ in the way that they perform change detection. Online property access traces depend on an external change notification mechanism whereas the offline variant computes changes by directly querying the latest version of the model. Given this difference, it follows that in the absence of a change notification mechanism, only the offline transformation mode is feasible. Apart from a practical consideration such as the availability of change notifications, the nature of the development environment is also an important factor. For example,

incremental online transformation may be more suitable in an environment where input model changes are frequent, and continuous and immediate change propagation is important.

Despite the effectiveness of property access traces as demonstrated through analytical arguments and empirical evaluation, they cannot be used if a property access recording mechanism is not in place or cannot be added to the M2T transformation language. In such cases, signatures can be a viable alternative. Although signatures have practical and theoretical limitations (Sections 4.4.1 and 4.4.1), they do not require a recording mechanism and hence can potentially be implemented for many more M2T languages than property access traces.

Threats to Validity.

The evaluation and experiments have considered two case studies which represent ends of a broad spectrum of M2T transformations; Pongo is relatively more complex than INESS with respect to the complexity of the transformation templates (i.e., Pongo templates comprise of complex filtering model queries), and INESS is more complex with respect to the size of its input model. Although the case studies are real-world M2T transformations, we recognise that further confidence can be derived from the evaluation if the experimentation included a wider range of case studies. However, as discussed in Section 6.1.4.1, not all potential case studies are implemented in EGL/EGX, and hence, they could not have been used for the experiments. An alternative strategy would be to automatically orchestrate synthetic M2T transformations by automatically generating source models, templates, followed by iterations of modifying the source models. This would potentially allow a greater exploration of the search space.

Automatic generation of models can be accomplished through tools such as Crepe [128]. However, modeling tools do not provide mechanisms for automatic template generation. Moreover, the generation of templates present the following challenges: 1.) generation of unique templates such that no two templates in the transformation contain exactly the same contents, 2.) varying the degree to which the generated templates exercise the source model in order to improve confidence in the coverage of the metamodel (ideally, some templates would access a small percentage of the model while some may fully exercise the input model), 3.) the generated templates should comprise model queries that range from simple accesses to relatively more complex queries such as filtering, 4.) the generated templates must be syntactically correct in order to be executable, 5.) ensuring that the automatically orchestrated transformations are going to be representative of real-world transformations. More generally, EGL/EGX does not have the facility to support automatic template generation and mutation, and as

at the time of writing (June 2016), no known modeling framework supports template generation.

6.5 Summary

In this chapter, we employed various evaluation methods to investigate the extent to which signatures and property access traces address the challenge of achieving scalable M2T transformation via automated and practical source-incrementality. Through analysis and experimentation on real M2T transformations, we have been able to identify the limitations of using signatures for source-incrementality. In particular, automatic signatures cannot guarantee the correctness of the output of a transformation engine, and user-defined signatures may be impractical because they require considerable developer effort. We also demonstrated that property access traces can achieve source-incrementality in a scalable and practical manner, for M2T languages that have the capability to monitor property accesses during template execution.

Chapter 7

Conclusion and Future Work

This thesis investigated scalability in MDE in the context of M2T transformations. Although MDE is described as a practical method of designing and improving software systems with increased productivity [9, 129], often MDE techniques such as model transformation do not scale. As such, much research has sought to address the scalability challenges of M2M transformations. However, since M2M transformations have distinct characteristics (e.g., the output of a M2M is a structured model while M2T typically produces text with arbitrary structure), both types of transformations present different types of challenges for incrementality (see Section 2.5.3). Little of the research on incremental transformation has been on M2T transformation, and M2T transformation tools do not support source-incremental transformations. This thesis has addressed this gap by exploring the following hypothesis:

> *Contemporary approaches to M2T transformations can be extended with novel and practicable techniques which enable correct and efficient source-incremental transformations without sacrificing the expressiveness of the M2T language.*
>
> *There exists a threshold point at which a source-incremental technique ceases to be more efficient than a non-incremental technique when executed on the same transformation.*

In light of the research hypothesis, the following objectives were defined in Section 1.4:

- To investigate scalability in the context of M2T transformations.
- To design algorithm(s) that will enable source-incrementality in M2T transformation languages.

- To implement the source-incremental algorithm(s) in an existing M2T language.
- To use the implemented source-incremental algorithm(s) to provide evidence that source-incrementality can be used to achieve scalable M2T transformations.

7.1 Thesis Contributions

The main contributions of this thesis in the context of the challenges of M2T transformations and the research hypothesis are summarised below.

Investigation of scalability in the context of M2T. Through a review of literature we identified scalability as a challenge in MDE, and investigated this challenge in the context of M2T transformations. However, as we were unable to find literature that analysed state-of-the-art of M2T in the context of scalability, one of the first steps taken during this research was to conduct a thorough analysis of contemporary M2T languages. We explored the current state of support for incrementality in M2T by analysing contemporary M2T languages (i.e., Acceleo, EGL, T4), and identified the lack of support for source-incrementality by M2T transformation tools as a major contributing factor to their inability to achieve scalable transformations. We also provided M2T specific definitions for the types of incremental model transformations. Furthermore, we argued that source-incremental transformation is the incremental transformation method most likely to improve the scalability of transformations because it reduces redundant re-computations during transformation re-execution. Our investigations led to the development of two different techniques, Signatures (Chapter 4) and Property access traces (Chapter 5) for enabling source incremental M2T transformations.

In contrast to typical incremental model transformation techniques which rely on model differencing, Signatures and Property access traces employ fundamentally different approaches to source-incrementality. Model differencing approaches detect input model changes by comparing the old and new versions of the input model which has two main shortcomings: it requires at least two model traversals, and the old version of the input model may not be available. Signatures and property access traces offer different strategies for change detection. Signatures detect input model changes by only comparing signature values. Property access traces detect changes by either querying the input model at transformation runtime or by accessing input model changes as the changes occur.

Signatures based source-incremental technique. The first of the techniques derives string proxies (*signatures*) for the output of template executions. A signature comprises necessary data that can be used to determine whether the re-execution of

a template will produce different output compared to the output of a previous execution of the template. Signatures are persisted between transformation executions, and whenever a signature evaluates to a value that is different from its previous value, only then is the corresponding template re-executed. As a result, only templates affected by input model changes are re-executed. Therefore, limiting the number of template re-executions, and reducing the transformation re-execution time. This signatures technique is premised on the assumption that re-evaluating a template proxy will require less time to execute compared to re-executing a template.

Signatures perform change detection and impact analysis at runtime. Performing change detection at runtime ensures that the transformation engine does not employ a potentially more computational expensive operation (e.g., model differencing) which would require loading two versions of an input model and two full model traversals. Signatures require only the most recent version of an input model and one model traversal to detect model changes, and perform impact analysis. We devised and implemented two strategies for generating signatures: automatic and user-defined. Automatic signatures derive their values from the dynamic text-outputting sections of templates. However, automatic signatures cannot be applied to M2T transformations that use parts of the input model only to control the execution path of a template. To address this drawback of automatic signatures, we implemented user-defined signatures. User-defined signatures are computed from expressions which are specified by transformation developers. Although user-defined signatures are not inhibited by the drawbacks of automatic signatures, they require developer intervention and can be difficult to maintain especially for large and complex transformations. In contrast, automatic signatures are easy to use because they are completely transparent to the developer and do not require developer intervention but they are limited to subset of M2T transformation that do not use model elements only to control template execution path.

Through empirical experiments we observed an average reduction of 45% in transformation execution time compared to non-incremental (batch) transformation. Furthermore, we identified subsets of M2T transformations and defined characteristics of such M2T transformations for which the signatures technique is amenable.

Property access traces for source-incremental M2T. The second technique (*property access traces*) produces structures that are based on recording access operations on model elements as templates are executed. The property access trace comprises model element features that are accessed during template executions along with template executions in which these model element features are consumed. Property access traces require a template execution observer mechanism for recording transformation execution information. Like signatures, the property access trace is persisted in non-volatile

storage between transformation executions. So, when the input model is modified, instead of re-executing templates, the transformation engine analyses the property access trace by querying the input model to determine whether the modification(s) applied to specific model elements are relevant to any of the transformation's template, and determine which templates require re-execution. A template is only re-executed if it consumes a model element feature whose value has been changed since the last execution of the transformation. We applied property access traces to different M2T transformations, and observed an average reduction of 60% in the time required to re-execute the transformation compared to the time required in non-incremental mode.

Incremental online transformation for immediate propagation of input model changes. Online transformations allow for immediate feedback and re-synchronisation of model dependent artefacts, and are particularly important in a development environment where changes are frequent and feedback is urgent. Although online incremental model transformation has previously been investigated in the context of M2M transformation [96], it had not previously been investigated for M2T transformations. We adapted property access traces to make them amenable to online M2T transformations. For online transformation, property access traces do not contain the value of recorded model element features. Online transformation using property access traces also required listening for input model changes via model editors. These two important modifications to property access traces eliminate the step of querying input models to determine input model changes. It is important to note that these changes did not alter the fundamental principle that underlies property access traces.

Investigation to determine whether source-incrementality enables scalable M2T transformations. We demonstrated the feasibility of signatures and property access traces by extending an existing M2T transformation language. Furthermore, we applied the proposed source-incremental techniques to real-life M2T transformations, and provided evidence through empirical evaluation that source-incrementality can be used to develop scalable M2T transformations. As a part of this work, we defined a set of criteria for source-incremental M2T and a set of strategies for evaluating a source-incremental approach against these criteria. Our evaluation criteria included testing the soundness, performance, and practicality of incremental techniques. Soundness describes the correctness, source-minimality and target-minimality. In addition, we proposed assessing the performance and scalability of incremental techniques along two dimensions: runtime and space complexity. With respect to runtime efficiency and space requirements, incremental M2T techniques should enable the propagation of input model changes to generated artefacts in less time than non-incremental techniques. In terms of space requirements, incremental M2T techniques should incur memory and disk space costs such that they are still practicable. Finally, we defined the practicality

of an incremental transformation as the extent to which the technique operates without intervention from the developer.

Through empirical evaluation we provided evidence that the source-incremental techniques proposed in this research are amenable to real life M2T transformations (e.g., the case studies presented in Chapter 6). For instance, during our empirical investigation of the INESS M2T transformation (which is the motivating example for this work), we observed a reduction in execution of up to 99% compared to the non-incremental execution of the transformation, while memory and space consumption were within 20% and 100% of the input model.

7.2 Future Work

There are different ways in which the proposed source-incremental techniques presented in this research work can be further enhanced and extended. Some of the identified areas of interests requiring further investigation are discussed below.

7.2.1 Exploit more space efficient approach to persistence

As discussed in Section 6.1.2, it is typical for incremental techniques in different areas of software engineering to impose a trade-off of space for runtime efficiency. Our implementations of signatures and property access traces used a relational database. In order to minimize space utilisation and avoid duplication of data, relational databases allow normalization of data. However, normalization tends to diminish the efficiency of reading data from the database because of join operations [130]. It will be interesting to investigate whether other persistence mechanisms, such as a graph database will incur less disk space cost, without compromising the performance of the store, i.e., the efficiency of writing and retrieving signatures and property access traces from the store. Graph databases offer faster data retrieval speeds for linked data because the latency of the graph query is proportional to the size of the graph that is exercised by a query.

7.2.2 Automatic replay of model evolution

Automatic replay of model evolution entails analysing two versions of a model and reconstructing modification operations which can be applied to either of the two versions in order to make them structurally equivalent. Potential applications of this mechanism include assessing the behaviour of transformation engines when certain types of changes are applied to models (e.g., when a root level element is modified, its impact

can trickle down to other model elements), and testing incremental model transformations techniques. This further investigation was motivated by our evaluation work on real-life M2T transformations, and by our illustration of online incremental M2T transformation. With regard to our case study requirement R3 (Section 6.1.4.1), it was important to re-construct model modifications when experiments are performed off site, and different versions of an input model are available. Currently, the re-construction of input model evolution is a manual process which includes writing modification scripts after identifying differences that exist between versions of an input model. Obviously, this can be a repetitive, painstaking, and error-prone process, especially when the two versions of the input model are substantially different.

An automated mechanism compares two input models, determines the differences between the models, and outputs not only the differences but constructs modifications statements that emulate the differences between the models. Thereafter, the modification statements can be replayed while relevant observations (e.g., change notifications) about the transformation are made. Arguably this automated mechanism will aid the process of testing model transformations.

7.2.3 Property access traces for M2M Transformation

Although M2M and M2T transformations are closely related, they differ significantly in that each type transformation exhibit some distinct characteristics, hence they have different concerns. For example, M2T transformations targets typically do not conform to a metamodel, and normally produce targets (text) with arbitrary structure. In contrast, M2M transformation targets are normally structured models. In addition, a typical M2M transformation engine supports rule dependency and often transformations are endogenous. A combination of rule dependency and endogenous transformation makes it difficult to readily apply property access traces to M2M languages. This is because an endogenous transformation modifies the model during transformation execution, and since there is inter-dependence among rules, the value of a previously accessed model element feature can be modified before being accessed by another rule. Nonetheless, further investigation is required to explore the possibility of applying source-incremental techniques (e.g., property access traces) to incremental M2M transformations.

7.2.4 Transaction boundaries for Online Transformation

Considering that in online mode, the transformation engine requires a way of determining when to re-execute a transformation after it has received changed notifications;

it is necessary to establish a transaction boundary, in order to ensure that the transformation is re-executed at the appropriate time. Determining transaction boundaries is challenging because the transformation engine waits while model editing is in progress, and it re-executes the transformation when editing has ended. However, distinguishing a temporary pause in model editing from an end to editing is non-trivial. Although in Chapter 5 we considered two approaches: immediate change propagation and user-driven control - further research is needed to identify the efficacy of other approaches ([131–133]) used in database transaction management.

7.2.5 Strategy for breaking large monolithic templates

Currently, M2T transformations that possess single large monolithic transformation templates do not lend themselves to source-incrementality because every change to the input model that affects the template, will cause the template to be re-executed in its entirety. In order to make large monolithic templates amenable to source-incremental techniques, they must be decomposed into a number of smaller templates whose outputs are merged at the end of the transformation. So, instead of re-executing a large template in its entirety, only smaller templates derived from it are re-evaluated upon changes. Whenever the output of any of the smaller templates is altered due to an input model change, its output is substituted into the appropriate section in the overall output file. This can be achieved by building a mechanism to support decomposing large monolithic transformation templates into smaller components.

7.3 Concluding Remarks

Software evolution pervades the entire history of software engineering. The challenges associated with propagating changes from one development artefact to other dependent artefacts has been the subject of many research endeavours; as has the need to devise effective methods for efficient and incremental change propagation. Incrementality is not just a concern of MDE, it applies to other areas of software engineering including databases, incremental compilers, system verification, etc. Achieving incrementality is vital for reducing redundant computation and increasing the scalability of software engineering tools and techniques.

However, achieving efficient and practical source-incrementality is challenging because it often imposes trade-offs; between time efficiency and automation (e.g., user-defined signatures require human intervention), between time efficiency and space consumption. For instance, more space (RAM and hard disk), is utilized for processing and persisting

trace information used for change detection and impact analysis compared to the space requirements of a batch transformation execution.

In addition to this, source-incremental transformation techniques are premised on the assumption that the underlying modelling frameworks support the use of non-reusable unique identifiers for model elements, and thus support establishing links between model elements and relevant transformation execution data, that are used for change detection and impact analysis. Similarly, source-incremental techniques that are based on change recording are reliant on the modelling framework to provide change notifications. Additionally, source-incremental techniques that are based on transformation execution recording are not amenable to M2T transformations which contain non-deterministic constructs.

This thesis has explored the state of the art of M2T transformations. We also devised and implemented two novel techniques for providing source-incrementality in M2T languages. In addition, we established a set of requirements which can be used to assess the effectiveness of incremental transformation techniques. Furthermore, through rigorous analysis and empirical experiments, we demonstrated the effectiveness of our proposed techniques. Finally, as a result of our findings, we have provided impetus for further research in the subject of incremental model transformation.

Appendix A

Pongo Experiment: Online Transformation

We performed this experiment to determine if the performance of property access traces in online mode is affected by increasing the magnitude of input model changes. We applied Pongo to manually-crafted input models which were modified by making two changes to each model element in a subset of the model elements. We observed that property access traces in online transformation mode out-performed non-incremental transformation until about 90% of the input model elements were modified (Table A.1).

	Non-Incremental		**Incremental**	
Changes (Elements #; %)	Templ. Invocations (#)	Time (s)	Templ. Invocations (#; %)	Time (s)
-	1000	5.10	1000	5.93
1 (0.1%)	1000	4.97	1 (0.10%)	0.25
10 (1%)	1000	5.79	10 (1.00%)	0.20
20 (2%)	1000	4.77	20 (2.00%)	0.51
100 (10%)	1000	5.62	100 (10.00%)	0.93
300 (30%)	1000	5.53	300 (30.00%)	1.81
600 (60%)	1000	4.94	600 (60.00%)	2.97
700 (70%)	1000	5.01	700 (70.00%)	3.55
800 (80%)	1000	4.98	800 (80.00%)	4.31
900 (90%)	1000	4.70	900 (90.00%)	4.84

TABLE A.1: Results of using non-incremental and incremental online M2T transformation for the Pongo M2T transformation, applied to increasingly larger proportions of changes to the source model.

Appendix B

Generating Synthetic Input Models for a Pongo Experiment

In this experiment, we constructed input models which are consumed by the Pongo transformation. The input models were constructed via a script (Listing B.1) that generated classes with identical structure (a constant number of attributes and no associations). The generated models comprised 1000 classes, and each class had 3 attributes. We annotate the first element in the model as the collection class for Mongo DB.

Following the creation of the input model, we execute the transformation, and in subsequent iterations we apply specific changes before re-executing the transformation in incremental mode. We used the EOL script in Listing B.2 to modify the class name and the age attribute of the class for a specific number of model elements. The number of modified model elements was steadily increased during each iteration.

Finally, in Listing B.3 we use an Ant script to orchestrate the creation of the input model, execution of the transformation, modification of the input model, and transformation re-execution steps.

```
1
2  var package = new EPackage;
3
4  package.name = "person";
5  package.nsURI = "person.model";
6  package.nsPrefix = "person";
7
8  var eString = new EDataType;
9  eString.name = "EString";
10 eString.instanceClassName = "java.lang.String";
11
12 for (j in 1.to(1000)) {
13   var firstAttr = new EAttribute;
14   firstAttr.name = "age";
15   firstAttr.setEType(eString);
16
17   var secondAttr = new EAttribute;
18   secondAttr.name = "dob";
19   secondAttr.setEType(eString);
20
21   var thirdAttr = new EAttribute;
22   thirdAttr.name = "name";
23   thirdAttr.setEType(eString);
24
25   var class = new EClass;
26   class.name = "Person" + j;
27   class.eStructuralFeatures.add(firstAttr);
28   class.eStructuralFeatures.add(secondAttr);
29   class.eStructuralFeatures.add(thirdAttr);
30
31
32   package.eClassifiers.add(class);
33   package.eClassifiers.add(eString);
34 }
35
36 var e = new EAnnotation;
37 e.source = "db";
38
39 package.eClassifiers.first.getEAnnotations.add(e);
```

Listing B.1: Input model constructed using EOL script

```
1
2  var n : Integer;
3  n = number_of_changes;
4
5  if(n = 1)
6    change = "b";
7  else if(n = 4)
8    change = "c";
9  else if(n = 5)
10   change = "d";
11 else if(n = 10)
12   change = "e";
13 else if(n = 20)
14   change = "f";
15 else if(n = 100)
16   change = "g";
17 else if(n = 300)
18   change = "h";
19 else if(n = 600)
20   change = "i";
21 else if(n = 700)
22   change = "j";
23 else if(n = 800)
24   change = "k";
25 else if(n = 900)
26   change = "l";
27 else if(n = 1000)
28   change = "m";
29
30
31 var st : Integer = 1;
32 var e : Integer = 0;
33
34 var ec : Sequence;
35 ec = EClass.all();  //gets all person objects in the source model
36
37 if(st <> 0){
38
39   for (i in Sequence{st..n}) {
40     var c = ec.random();
41     if(ec.size() > 0){
42       e = ec.indexOf(c);
43       var a = c.EAllAttributes;
44       a.first.name = a. first.name + change;
45       c.name = c.name + change;
46       ec.removeAt(e);
47     }
48     else
49       break;
50   }
51
52 }
```

Listing B.2: Input model modified using EOL script

```
<project name="project">
  <taskdef resource="net/sf/antcontrib/antcontrib.properties"/>

  <target name="LoadPersonModel">
    <epsilon.emf.loadModel name="ECore" modelfile="person-model.ecore" metamodeluri="
     qdmodel" read="false" store="true" />
  </target>

  <target name="LoadEcoreModel">
    <epsilon.emf.register file="src/metamodel/Ecore.ecore" />
    <epsilon.emf.loadModel name="Ecore" modelfile="src/metamodel/Ecore.ecore" metamodeluri
     ="http://www.eclipse.org/emf/2002/Ecore" read="true" store="false" />
  </target>

  <target name="createModel" depends="LoadPersonModel">
    <epsilon.eol src="src/scripts/create_model.eol">
      <model ref="Person" />
    </epsilon.eol>
  </target>


  <target name="non-incr-transformation" depends="LoadPersonModel">
    <epsilon.egl incremental="false" src="src/templates/pongo.egx" >
      <model ref="Person" />
    </epsilon.egl>

    <epsilon.eol src="src/scripts/modify_model.eol">
      <parameter name="number_of_changes" value="${var}" />
      <model ref="Person" />
    </epsilon.eol>
  </target>

  <target name="run-non-incr-transformation">
    <foreach list="1,4,5,10,20,100,300,600,700,800,900,1000,-1" param="var" target="non-
     incr-transformation">
    </foreach>
  </target>


  <!-- incremental execution -->
  <target name="incremental-transformation" depends="LoadPersonModel">
    <epsilon.eol src="src/scripts/modify_model.eol">
      <parameter name="number_of_changes" value="${var}" />
      <model ref="Person" />
    </epsilon.eol>
  </target>

  <target name="run-incremental-transformation">
    <foreach list="1,4,5,10,20,100,300,600,700,800,900,1000,-1" param="var" target="
     incremental-transformation-1">
    </foreach>
  </target>

  <target name="incremental-transformation-1" depends="LoadPersonModel">
    <epsilon.egl incremental="true" incrementalid="pongo-1" src="src/templates/pongo.egx"
     >
      <model ref="Person" />
    </epsilon.egl>

    <epsilon.eol src="src/scripts/modify_model.eol">
      <parameter name="number_of_changes" value="${var}" />
      <model ref="Person" />
    </epsilon.eol>
  </target>

</project>
```

Listing B.3: Ant script used to orchestrate model creation, modification, and transformation execution

Appendix C

Feature based user-defined Signatures Implementation

This appendix contains the implementation of the featured based user-defined signatures in Chapter 4. By using this feature, user-defined signatures can be correctly specified without the rigour of specifying a potentially long list of model element features nor the concerns of specifying a correct user-defined signature expression. The *asSignatureFromPrimitive* method takes as arguments, the model element for which the value of its specified attribute is to be computed, and the name of a non-reference attribute of the model element, which is an EStructuralFeature. The values of non-primitive eStructuralFeatures that are references to the model element are computed in the *asSignatureCall* method which takes three arguments (i.e., a reference (*EObject obj*), an array of references to the reference (*visitedRefs*), and a depth (an integer variable)). *visitedRefs* is a list of model elements that are references to the model element that itself is a reference to the model element (subject model element) whose signature is being computed. This reference list contains unique model elements whose signatures have been computed as part of the signature of the subject model element. The *depth* argument is used to prevent visiting all references in the model during computation. For example, a depth of 1 limits the computation of the signature to direct references of the subject model element. Finally, the *asSignature* method takes only one argument (i.e., the model element for whose signature is to be computed) and returns a list of Strings computed from executing the *asSignatureCall* method.

```
1
2  package org.eclipse.epsilon.egx.manualsignature;
3
4  import java.util.ArrayList;
5  import java.util.Collection;
6  import org.eclipse.emf.ecore.EAttribute;
7  import org.eclipse.emf.ecore.EEnumLiteral;
8  import org.eclipse.emf.ecore.EObject;
9  import org.eclipse.emf.ecore.EReference;
10 import org.eclipse.emf.ecore.EEnum;
11 import org.eclipse.emf.ecore.EStructuralFeature;
12 import org.eclipse.emf.ecore.EcoreFactory;
13
14 public class ManualSignature {
15
16   public String asSignatureFromPrimitive(EObject obj, EStructuralFeature attr) {
17     if(attr != null) {
18       if(attr.eClass().getName().equals("EEnumLiteral"))
19         {
20           return ((EEnumLiteral)attr).getLiteral();
21         } else {
22             return obj.eGet(attr) + "";
23         }
24     }
25     return "";
26   }
27
28   public ArrayList<String> asSignatureCall(EObject obj, ArrayList<Object> visitedRefs, int
       depth) {
29     ArrayList<String> signature = new ArrayList<String>();
30     if (obj == null || depth > 1) {
31       return null;
32     }
33
34     depth = depth + 1;
35     visitedRefs.add(obj);
36
37     if (obj.eClass().getName() == "EGenericType")
38       return new ArrayList<String>();
39
40     for(EAttribute attr : obj.eClass().getEAllAttributes()) {
41       if (! attr.isDerived() ) {
42         if (attr.isMany()) {
43           ArrayList<String> signaturesOfAllValues = new ArrayList<String>();
44           for (EObject val : attr.eContents()){
45             signaturesOfAllValues.add(this.asSignatureFromPrimitive(attr,(EAttribute)val))
      ;
46           }
47           signature.addAll(signaturesOfAllValues);
48         } else {
49           signature.add(this.asSignatureFromPrimitive(obj, attr));
50         }
51       }
52     }
```

```
53
54      for (EReference r : obj.eClass().getEAllReferences()) {
55        if (! r.isDerived()) {
56          if(r.isMany() ) {
57            ArrayList<EObject> refs = new ArrayList<EObject>();
58            refs.addAll((Collection<? extends EObject>) obj.eGet(r));
59            for(EObject ref : refs) {
60              if (! visitedRefs.contains(ref) && ref != null) {
61                ArrayList<String> refSigHold = new ArrayList<String>();
62                refSigHold = this.asSignatureCall(ref, visitedRefs, depth);
63                signature.addAll(refSigHold == null ? new ArrayList<String>() : refSigHold);
64              }
65            }
66          } else {
67            EObject ref = (EObject) obj.eGet(r);
68            if (! visitedRefs.contains(ref) && ref != null) {
69              ArrayList<String> refSigHold = new ArrayList<String>();
70              refSigHold = this.asSignatureCall(ref, visitedRefs, depth);
71              signature.addAll(refSigHold == null ? new ArrayList<String>() : refSigHold);
72            }
73          }
74        }
75      }
76
77      return signature;
78
79    }
80
81    public ArrayList<String> asSignature(EObject o) {
82      return this.asSignatureCall(o, new ArrayList<Object>(), 0);
83    }
84
85  }
```

Listing C.1: Feature-based user-defined signatures implemented in Java

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