

Triple Graph Grammars or Triple Graph Transformation Systems?*

A Case Study from Software Configuration Management

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Abstract. Triple graph grammars have been used to specify consistency maintenance between inter-dependent and evolving models at a high level of abstraction. On a lower level, consistency maintenance may be specified by a triple graph transformation system, which takes care of all operational details required for executing consistency maintenance operations. This paper presents a case study from software configuration management in which we decided to hand-craft a triple graph transformation system rather than to generate it from a triple graph grammar. The case study demonstrates some limitations concerning the kinds of consistency maintenance problems which can be handled by triple graph grammars.

1 Introduction

Model transformations play a key role in model-driven engineering. In the most simple case, a transformation of some source model s into some target model t may be performed automatically by a model compiler. If there is no need to edit t , model evolution (of s) may be handled by simply compiling s once more. However, in general it may not be possible to generate t from s completely automatically, both s and t may evolve, and changes may have to be propagated in both directions (consider, e.g., round-trip engineering between a requirements model and a design model).

In principle, model transformations may be programmed in an ordinary programming language such as Java. This approach is still followed frequently, but clearly a more high-level approach is desired: Model-driven engineering should be applied not only to the target process to be supported, but also to the process of developing model transformations itself.

Many formalisms have been proposed for defining model transformations, including e.g. QVT [1] in the context of object-oriented modeling. In this paper, we focus on *graph transformations*: Graphs may represent models in a natural way; graph transformation rules describe modifications of graph structures in a declarative way. Furthermore, there is a comprehensive body of theories, languages, tools, and applications (see e.g. the handbook series on graph grammars [2–4]).

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For maintaining consistency between interdependent and evolving models, a graph transformation system is required which deals with at least two graphs, namely the *source graph* s and the *target graph* t ¹. For incremental change propagation, a *correspondence graph* c is placed in between s and t for maintaining *traceability links*. This results in a *triple graph transformation system (TGTS)*, the rules of which define source-to-target and target-to-source transformations as well as actions for checking consistency and repairing inconsistencies.

Developing a TGTS is still a tedious and laborious task: First, in addition to the generation of graphs, modifications and deletions have to be specified explicitly. Second, each direction of transformation has to be specified explicitly - as well as rules for checking consistency and establishing correspondences. Therefore, *triple graph grammars (TGG)* [5, 6] have been proposed to make the task of specifying inter-model consistency maintenance easier. From a high-level TGG dealing only with the synchronous generation of graphs, a more low-level TGTS for inter-model consistency maintenance may be generated.

In this paper, we explore the alternatives of *hand-crafting a TGTS* versus defining a TGG and *generating a TGTS* from the TGG. To this end, we present a *case study* which we performed in the *MOD2-SCM* project (*MODEl-Driven MODular Software Configuration Management System* [7]). The project employs Fujaba [8] as modeling language and tool, but the discussion in this paper is not specific to Fujaba. The case study deals with a recurring problem in SCM, namely the synchronization of repositories and workspaces, which involves bidirectional incremental propagation of changes. We present a hand-crafted TGTS for this application and discuss the alternative of generating the TGTS from the TGG.

2 Background

A *directed, typed, attributed graph* consists of typed nodes which are decorated with attributes and are connected by typed, directed, binary edges. In terms of object-oriented modeling, a node corresponds to an object, and an edge corresponds to a binary link with distinguishable ends. A *graph grammar* is composed of a graph schema, which defines types of nodes, edges, and attributes, a start graph, and a set of *productions* which are used to generate a set of graphs forming a graph language. Thus, a graph grammar is concerned only with the generation of graphs. In contrast, a *graph transformation system* is made up of a set of *graph transformation rules*, which describe arbitrary graph transformations including deletions and modifications.

The TGG approach is illustrated in Figure 1. A *triple graph* consists of a *source graph* s , a *target graph* t , and a *correspondence graph* c . The nodes of c , which are called *link nodes*, are connected to nodes of s and t , respectively. A *triple graph grammar (TGG)* declaratively specifies consistency relationships between source and target graph. The TGG designer need only define generative *triple rules* which describe synchronous extensions of source, target, and correspondence graph. From each synchronous triple rule, three *directed rules* may be generated (if required): A *forward*

¹ For the sake of simplicity, our notation does not distinguish between a model and its graph for its representation.

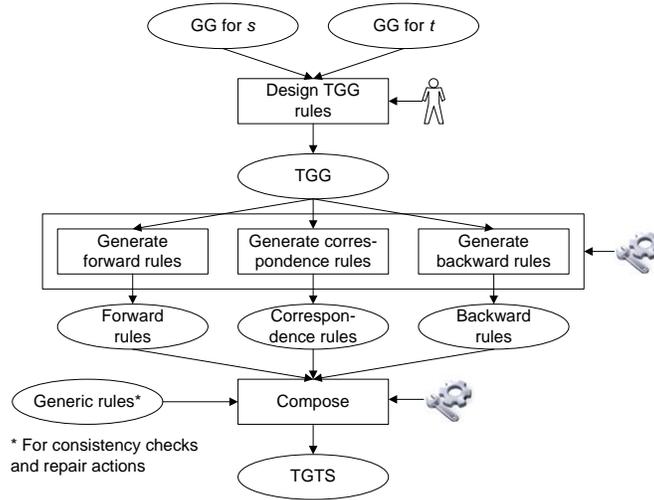


Fig. 1. The TGG approach

rule assumes that s has been extended, and extends c and t accordingly; likewise for *backward rules*. A *correspondence rule* extends c after s and t have been extended with corresponding graph structures. Like triple rules, directed rules are *monotonic*, i.e., they describe graph extensions. Directed rules are required when s , t , and c have not been changed synchronously (e.g., when different users concurrently edit s and t).

A *triple graph transformation system (TGTS)* is composed of a set of *triple graph transformation rules* for inter-model consistency maintenance. These rules describe not only extensions, but also deletions and modifications. A TGTS may be *hand-crafted*, i.e., created manually by a TGTS designer. However, in the TGG approach the TGTS is *generated* from the TGG. In addition to the directed rules explained above, further rules are needed which deal with modifications and deletions having been performed in s and t . To this end, *generic rules* are required which perform *consistency checks* and *repair actions*. Generic rules and generated directed rules jointly constitute the overall TGTS. The TGTS may also include a control structure for efficient graph traversal in order to speed up the execution of the consistency maintenance algorithm.

The following alternatives are discussed in this paper: a) hand-crafting a TGTS, and b) generating a TGTS from a TGG. Of course, hand-crafting a TGTS pays off only when generation from a TGG does not work appropriately. This raises the question to which classes of problems the TGG approach may be applied successfully. The case study presented below contributes to answering this question.

3 Case Study

In this section, we present a *case study* which we explored in the context of the *MOD2-SCM* project [7]. The overall goal of this project is to develop a *model-driven product line* for *software configuration management (SCM)*. The project was motivated by the

following shortcomings of state-of-the art systems: First, development of an SCM system is a laborious task, which may be leveraged by model-driven development. Second, the underlying models are implicit and hard-wired into SCM systems, which are difficult to adapt and to change. Finally, SCM systems share similar and recurring concepts; thus, a product-line approach promises to further reduced development effort.

In the context of developing SCM systems, a recurring problem to be solved consists in the *synchronization* between *repositories* and *workspaces*: Versioned software objects are archived in a repository. Software engineers check versions out into a workspace, change them, and check the changed versions back into the repository. Thus, synchronization between repositories and workspaces involves *bidirectional* and *incremental change propagation*.

The case study was inspired by open source SCM systems such as Subversion [9] or CVS [10]. In both systems, a repository stores versions of files which are organized into directories. A workspace consists of a tree of directories and files. In a workspace, changes are performed by overriding. In contrast, when a changed file is committed into the repository, a new version of the file is created.

In the model we built, both files and directories are versioned in a uniform way. The version history of each file system object is represented by a *version tree*. A version of a directory uniquely determines the versions of its components. While file system objects are organized into strict hierarchies (trees), the hierarchy of file system object versions allows for sharing.

Synchronization between repositories and workspaces is supported by the following commands which, when applied to directories, are propagated to all components: `add` prepares a file system object for a commit into the repository. `commit` commits a file system object into the repository. For an added file system object, an initial version is created in the repository. For a changed versioned file system object, a successor version is created. `checkout` creates a fresh copy of some file system object version in the file system. `update` propagates changes from the repository into the workspace. Unmodified copies of outdated versions are replaced with copies of new versions; modified copies are not updated to prevent the loss of local changes. Finally, `checkStatus` analyzes the consistency between repository and workspace. File system objects are marked as created, deleted, modified, moved, or out of date.

An example is given in Figure 2. The scenario starts with a repository which is initially empty and a small file system hierarchy (a). In step 1, `add` is applied to the hierarchy rooted at `d1`. All objects (files or directories) of this hierarchy are scheduled for commit. Adding is implemented by creating link objects and attaching them to the file system objects. In step 2, `commit` is used to import the file hierarchy into the repository. For each file system object, both a versioned object and its initial version are created. Furthermore, the hierarchy is mirrored in the repository both at the object and the version level. In step 3, a part of the hierarchy (with root `d2`) is exported into another workspace with `checkout`. In `ws2`, the text content of `f2` is updated, and the name of `f3` is changed into `f4`. Finally, in step 4 the changes in `ws2` are committed. This causes new versions of both files to be created. Please note that the file names of different versions may differ. Furthermore, a new version of the directory `d2` is created which includes the new versions of the changed files. An `update` propagates the changes from the reposi-

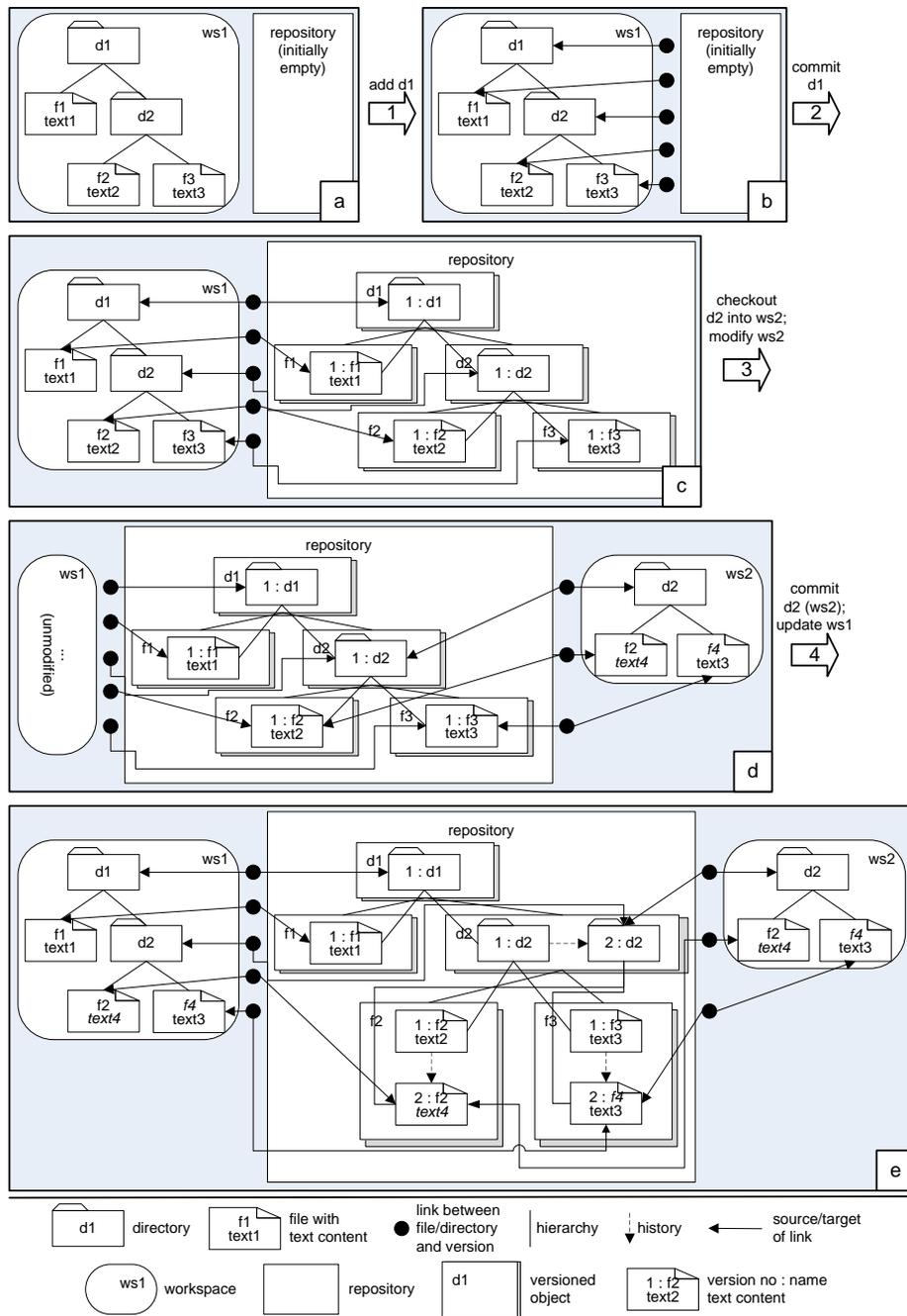


Fig. 2. Example

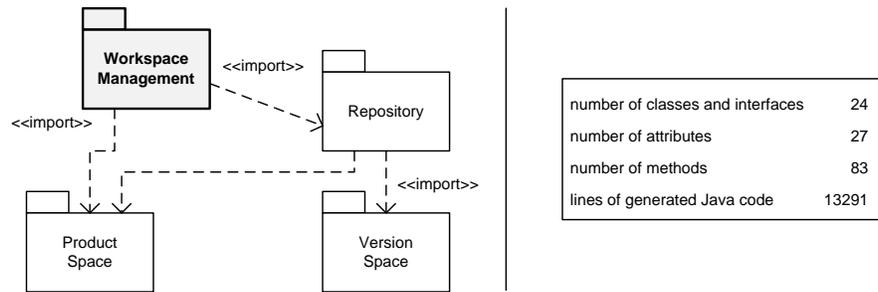


Fig. 3. Package diagram (left) and model size (right)

tory to ws2; all files and directories now refer to the current versions. Please note that due to the lack of space we have not shown *structural variations* caused by moves and deletes.

4 A Triple Graph Transformation System

In this section, we present the approach which we decided to follow in our case study. Synchronization of repositories and workspaces is modeled with the help of a *hand-crafted TGTS*. Generating a TGTS from a TGG is discussed in the next section.

4.1 Modeling Language

The TGTS was created with the help of the object-oriented modeling language and environment *Fujaba* [8]. In *Fujaba*, nodes and edges are represented as objects and links, respectively. Types of nodes and edges are defined by *class diagrams*. The behavior of objects and links may be modeled by story patterns and story diagrams (see below). Models written in *Fujaba* are executable (compiled into Java code).

Story patterns are UML-like communication diagrams which can be used to represent graph transformation rules. A story pattern consists of a graph of objects and links. A graph transformation rule is expressed by marking graph elements as deleted or created. Furthermore, conditions may be defined for attribute values, and the values of attributes may be modified. Finally, methods may be called on objects of the story patterns. Thus, story patterns constitute a uniform language construct for defining graph queries, graph transformations, and method calls.

Programming with story patterns is supported by *story diagrams*, which correspond to interaction overview diagrams in UML 2.0. A story diagram consists of story patterns which are arranged into a control flow graph. Story patterns appear in-line in nodes of the control flow graph. Each story diagram is used to implement a method defined in the class diagram.

4.2 Model Architecture

Figure 3 shows a *package diagram* on the left and lists data on the overall model size on the right. Each *package* contains one class diagram and a set of story diagrams for

the methods introduced in the classes of the package. A dashed line labeled with *import* denotes an *import* relationship. An unlabeled dashed line represents a *dependency* (the dependent package may have to be modified if the target package is changed).

Using the terminology of [11], we distinguish between a *product space*, which is composed of the elements to be submitted to version control, and a *version space*, where the evolution of these elements is represented. In the context of this paper, the product space consists of the file system hierarchy. The package `VersionSpace` introduces classes for managing the evolution of versioned objects. In the version model of the case study, the versions of a versioned object are organized into a history tree. The package `Repository` provides classes for versioned files and directories, based on the packages `ProductSpace` and `VersionSpace`. Composition hierarchies are defined on both object and version level. The packages mentioned so far will not be discussed further. Rather, we will focus on the package `WorkspaceManagement` (for the synchronization between the repository and workspaces, see next subsection).

It is important to note that we use *import* relationships in a much more restricted way than permitted in the UML standard. According to the standard, an *import* merely extends the set of elements visible in the importing package and allows for modifications of imported elements (see [12], p. 143). In our model, imported packages are *used* rather than *modified*: In the TGTS (i.e., in the package `WorkspaceManagement`), we merely add associations to imported classes (which is needed to represent traceability relationships). We avoid defining subclasses of imported classes; otherwise, applications operating on the imported data structures might have to be modified. Furthermore, change operations are realized by calling the methods of imported classes rather than by directly modifying the respective graphs (which might result in consistency violations).

4.3 Class diagram

Figure 4 shows the class diagram for the package `Workspace Management`. Classes imported from other packages are displayed with collapsed attributes and methods sections (left-hand and right-hand side). The class `WorkspaceManager` provides the external interface of methods for synchronizing repositories and workspaces (facade pattern). The interface includes those commands which were explained in Section 3.

Synchronization between repositories and workspaces is realized with the help of a *correspondence graph*, which is composed of *link objects* being connected to one source object and one target version, respectively. The abstract class `Link` provides a set of methods corresponding to the exported methods of `WorkspaceManager`, and a set of auxiliary methods. Furthermore, each link object carries a set of boolean attributes indicating the state of the link: In state *created*, the target of the link does not yet exist. In state *deleted*, the source of the link has been destroyed. In state *modified*, both source and target exist, and the source has been modified in the workspace. In state *moved*, the source has been moved to a different location. In state *outOfDate*, a new version of the target is available. Finally, in state *updated*, the source has been updated to a new version of the target, but this change has not been committed yet at the next higher level. Please note that these attributes are not mutually exclusive (e.g., a link object can be both out of date and modified).

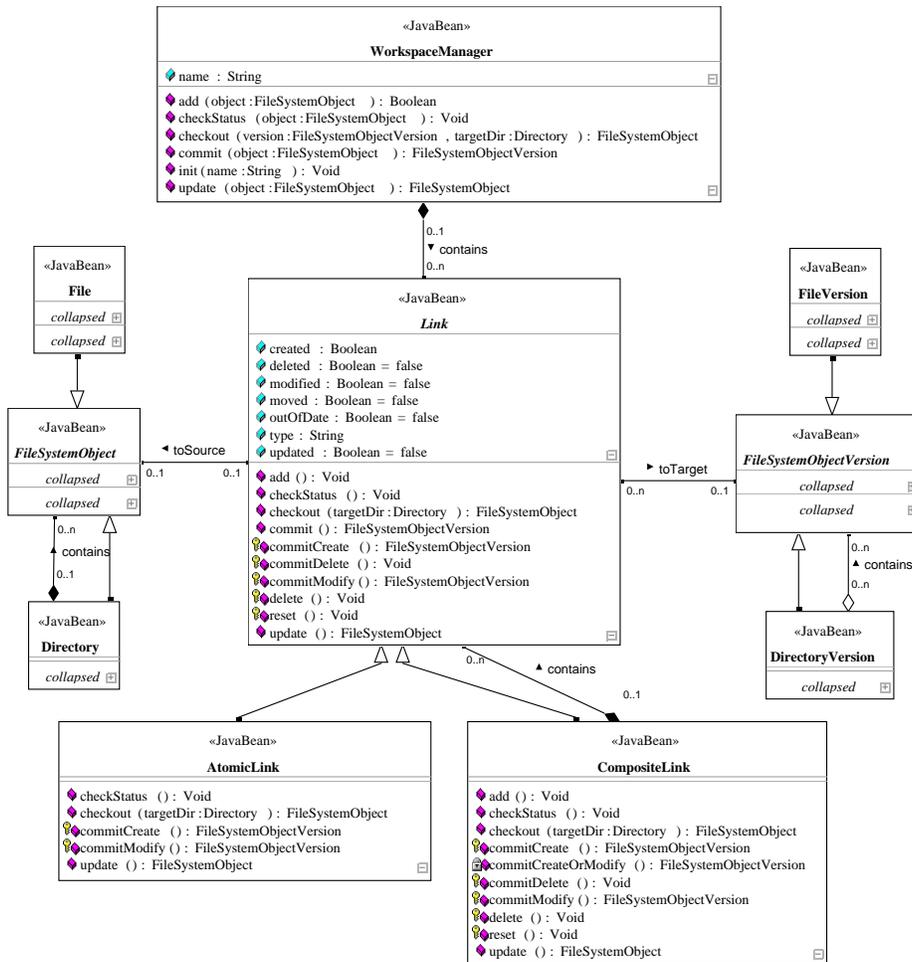


Fig. 4. Class diagram for the package Workspace Management

Link objects are organized into a composition hierarchy in a similar way as file system objects (composite pattern). When the workspace is consistent with the repository, the composition tree for the link objects agrees with the composition tree of the file system objects in the workspace. The algorithms for synchronizing repositories and workspaces traverse the composition hierarchy. Since they are attached to the class Link and its subclasses, the classes of the imported packages need not be extended or modified.

4.4 Operations

To illustrate the style of modeling adopted in the TGTS, we present three examples of methods for synchronizing repositories and workspaces. All sample methods are at-

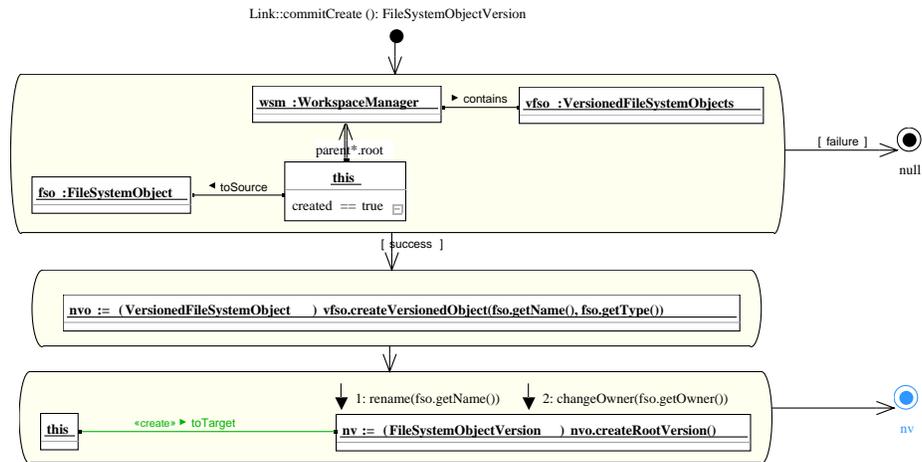


Fig. 5. Story diagram for committing a creation

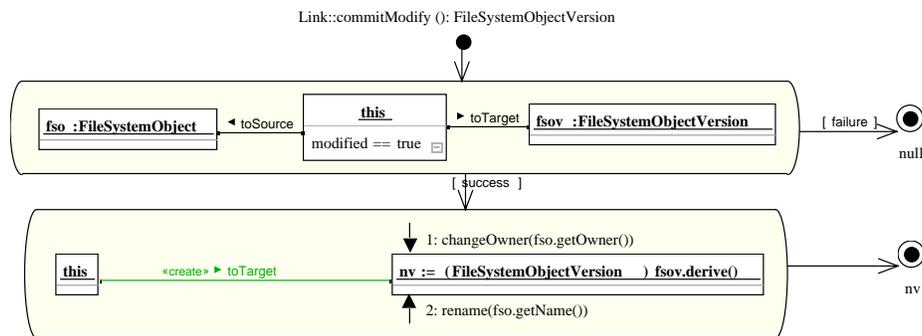


Fig. 6. Story diagram for committing a modification

tached to the class Link and perform only those parts of the synchronization which can be handled at this general level. The methods are redefined in the subclasses. Furthermore, all methods presented below assume that the values of state attributes are up to date (i.e., a status check must have been run before performing the synchronization).

Figure 5 shows the story diagram for committing the creation of a new file system object. The first story pattern checks the state of the link object and locates the root of the repository via the workspace manager. In the second step, a new versioned object is created. The third step creates the root version of this object, sets its name and its owner, and connects the new version to the link object.

The story diagram of Figure 6 is invoked when a file system object is already under version control and has been modified in the workspace. In the first step, the state of the link object is checked, and both ends are retrieved. In the second step, a successor version of the old target is created, and the link object is redirected to the new target.

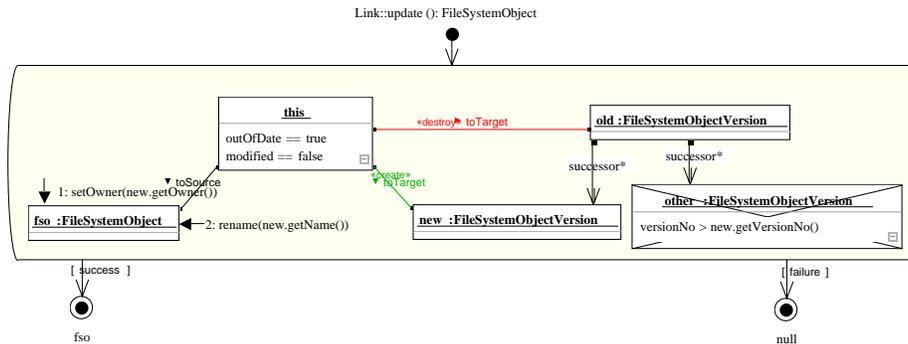


Fig. 7. Story diagram for performing an update

Please note that creation of a new toTarget link implies the deletion of the old link as a side effect.

The story pattern of Figure 7 handles change propagation from the repository into the workspace. The link object must be both outOfDate and not modified; the latter condition prevents that changes in the workspace are overwritten inadvertently. The link object is redirected to refer to the most recent (transitive) successor of the old target. This is ensured by the negative application condition (crossed object): There must be no other successor with a higher version number. In the course of the update, the name and the owner of the file system object are copied from the new target version.

These examples illustrate the style of modeling: All story diagrams manipulate only the link objects and their embeddings directly. All changes in the repository and the workspace are affected by method calls only. As a consequence, the consistency of the repository and the workspace is maintained by the operations exported from the respective packages (ProductSpace and Repository).

5 A Triple Graph Grammar?

This section discusses the application of the TGG approach to our case study. To this end, we modeled some sample TGG rules in Fujaba. In the presentation below, we describe several conceptual problems which we encountered.

5.1 Synchronous Rules

The first step of the TGG approach — defining a set of triple rules — is illustrated in Figure 8. The figure displays three rules which handle the creation of a subdirectory². Each rule is applied to a complex link both ends of which are already present. All rules perform the same extensions on the source graph and the correspondence graph: A subdirectory is created if there is no file system object of the same name; furthermore, a sublink is created and connected to the new subdirectory. The rules differ with respect

² The creation of a file in a directory may be handled analogously.

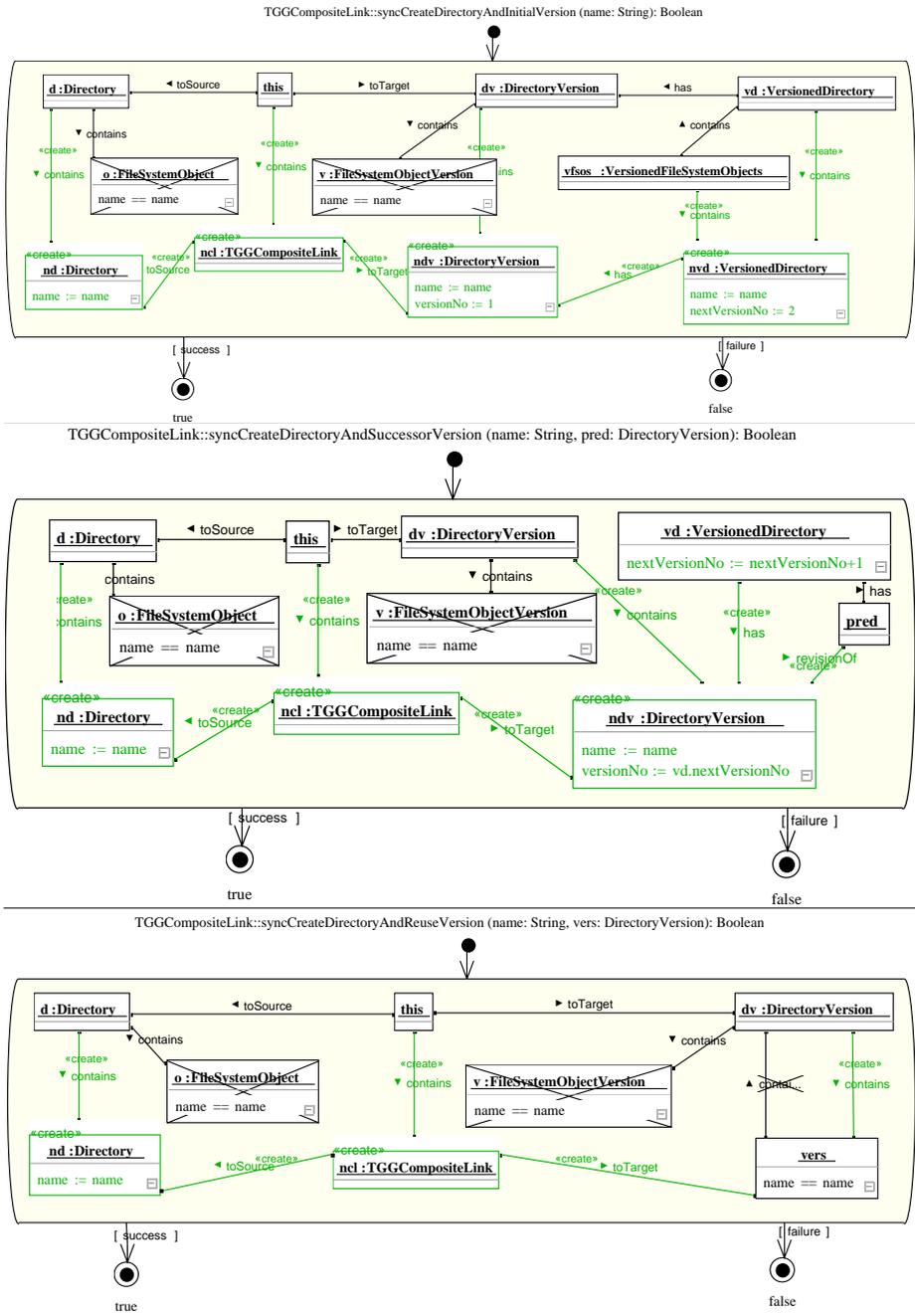


Fig. 8. Synchronous rules for creating directories and directory versions

to the target graph. The rule set is designed in such a way that all structures which may occur in the repository can be generated (version trees for the evolution history, acyclic graphs for the composition hierarchy).

The style of modeling employed in the TGG is quite different from the style of the TGTS (see Figures 5–7). The TGG consists of attributed graph productions which are partially obtained by copying productions from the graph grammars for the source graphs and the target graphs, respectively. This kind of reuse is called *white-box reuse*. In contrast, in the TGTS source and target graph may be read, but they may be updated only through method calls. This kind of reuse is called *grey-box reuse*.

The first rule creates a directory in the workspace along with a versioned object and an initial version in the workspace. The attribute `nextVersionNo` is a counter which stores the next available version number at the versioned object. The second rule creates a successor version, which is assigned the next available version number, and increments the counter. Using only the first and the second rule, only composition trees may be created in the repository. In the third rule, a directory is created in the workspace and related to a reused version which is added to the version of the parent directory.

Unfortunately, the third rule (`CreateDirectoryAndReuseVersion`) does not operate correctly. After its execution, the composition hierarchy rooted at the new directory in the workspace is empty, but this does not necessarily apply to the reused version at the other end of the link. If the composition hierarchy below the reused version is not empty, the generation process will “get of out sync”. We will return to this problem in the next subsection.

5.2 Directed Rules

While synchronization of repositories and workspaces involves bidirectional change propagation and thus requires forward and backward rules, *correspondence rules* are of little use: An analysis tool which discovers correspondences between repositories and workspaces and extends the correspondence graph accordingly is not required in our case study. The status check, which analyzes consistency between repository and workspace, merely determines the status of already existing link objects. Thus, it belongs to the category of consistency checks to be discussed in the next subsection. Please note that the lack of need for correspondence rules is not a serious problem: If they are not needed, they are simply not generated.

Forward rules are obtained from synchronous triple rules by converting created elements in the source graph into elements of the left-hand side. For the rules of Figure 8, this means that the directory `nd` and its composition link have to be moved to the left-hand side (i.e., they must already be present to apply the rule).

The operational behavior of the generated forward rules does not match the requirements of our case study. Since all rules shown in Figure 8 are identical with respect to the source graph and the correspondence graph, the generated rules are in *conflict*: A new subdirectory can be transformed by any of these rules, and applying one rule invalidates the other choices. Since the rules have different effects, the generated TGTS is *non-deterministic*, resulting in an integration tool which requires user interaction. In contrast, the commands introduced in Section 3 operate in a *deterministic* way. For a

new file system object, the user may not deliberately choose either to create a new versioned object and its root version, or to create a successor version, or to reuse an already existing version. Rather, only the first option is available for a new file system object. A successor version is created when the file system object has already been linked to a version in the repository and has been changed locally in the workspace. Finally, a version is reused when a new version of the parent directory has been created, the child object is already under version control and has not been changed in the workspace.

Similar problems occur in the generation of backward rules: All *backward rules* would create a file system object in the workspace; yet, they differ with respect to their contexts in the target graph. Again, conflicts may occur (between the rule for reusing a version and the other rules), but in this case the choice of the backward rule to be applied does not make any difference. In fact, the generated backward rules should be consolidated into just one rule which handles the insertion of a file system object into a workspace; the differing contexts are immaterial.

To conclude this subsection, let us return to the final remark of the previous subsection: The synchronous rule for reusing a version does not operate correctly (see above). As already mentioned, the composition hierarchy underneath the reused version is not mirrored in the workspace after having applied this rule. This problem could be fixed by calling a method which would populate the workspace with a copy of the hierarchy stored underneath the reused directory version. Fujaba does allow for method calls in story patterns (as has been demonstrated in Section 4). However, adding a method call would break the TGG approach (the rule would no longer be a single graph production; rather, it would correspond to a programed graph transformation).

This indicates a fundamental problem which we encountered in our case study. The TGG approach assumes that forward and backward transformations operate *symmetrically*: From a single synchronous rule, both a forward rule and a backward rule are derived. Using forward rules only, the target can be generated from the source; vice versa for backward rules. However, forward and backward transformations behave differently in our case study. For example, when the content of a file is modified in the workspace, a new version is created in the repository. In contrast, when the new version is propagated into another workspace by running an update command, the file in the workspace is overridden. Furthermore, composition hierarchies are treated differently in the workspace (tree) and in the repository (acyclic graph). As a consequence, an acyclic graph is *unfolded* into a tree when it is exported into a workspace, and a tree in the workspace is *folded* into an acyclic graph when changes are committed into the repository.

5.3 Consistency Checks and Repair Actions

One of the most important goals of the TGG approach is to relieve the modeler from the burden of specifying modifications and deletions. Since the TGG rules define only graph extensions, this abstraction works only when all operations concerning modifications and deletions can be derived automatically. To this end, generic support for *consistency checks* and *repair actions* is required (see Figure 1). Unfortunately, to the best of our knowledge providing such checks and repair actions in a generic way still constitutes an open research problem.

In our case study, consistency checks are performed in the `checkStatus` command. Some parts of the status checks could be covered by a generic approach, e.g., difference between values of attributes such as file names and file contents. However, there are some parts which are highly domain-specific. For example, changes in some file system object need to be propagated bottom-up to the root such that new versions in the repository may be created top-down in the course of a commit. Furthermore, the status check has to recognize updates in the repository that have to be propagated into the workspace. This is a domain-specific requirement, and there is no triple rule from which we could derive such a check. Repair actions are performed in the commands for synchronization, namely `update` and `commit`. Again, these repair actions are domain-specific. For example, when a file in the workspace is deleted, its corresponding version in the repository is not deleted, as well. Rather, a new version of the parent directory is created which does not contain this file version.

6 Related Work

The overall goal of the MOD2-SCM project is to provide a model-driven product line that allows to construct a wide range of customized SCM systems with acceptable effort. These goals are related to a few research projects which were dedicated to the development of a *uniform version model*. Both ICE [13] and UVM [14] proposed rule-based generalizations of conditional compilation as a low-level, common base mechanism. To date, only a few approaches have been dedicated to *model-driven development of versioning systems* [15–17]. However, all of these approaches are confined to structural models inasmuch as the behavior is hard-coded into the respective system.

Triple graph grammars were introduced as early as 1994 [5]. The QVT standard [1], which was developed much later, is based on similar concepts. In the context of this paper, it is interesting to note that QVT defines both a high-level declarative and a more low-level operational language. Several projects were built upon the concepts of TGGs, but actually developed a hand-crafted TGTS [18, 19]. Frameworks supporting code generation for TGGs have emerged only recently [20–22]. Surveys of the current state-of-the-art in TGGs are given in [6, 23]. In [24], research challenges and open problems are discussed. Four design principles for TGGs are postulated: completeness, consistency, efficiency, and expressiveness. The case study presented in this paper primarily challenges the expressiveness of TGGs, particularly because the required forward and backward transformations do not operate symmetrically.

7 Conclusion

We presented a case study of bidirectional incremental change propagation and consistency maintenance. The case study was performed in the MOD2-SCM project, which aims at developing a model-driven product line for SCM. In this context, it is important to apply model-driven engineering in a systematic way. The model-driven product line itself may be viewed as a large case study which hopefully contributes to gathering experiences and improving the current state of model-driven engineering.

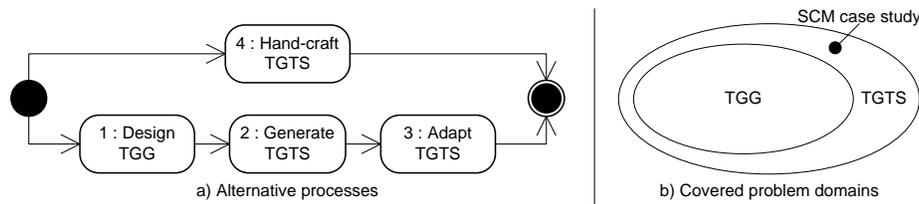


Fig. 9. Triple graph grammars or triple graph transformation systems?

For the synchronization between repositories and workspaces, we discussed the alternatives of hand-crafting a TGTS or generating a TGG (Figure 9a). From a pragmatic point of view, we look for a shortest path from the problem to the solution. Following the TGG process sketched in Figure 1, the costs of step 2 would be zero (automatic step) and step 3 would be obsolete. Unfortunately, generating a TGTS from a TGG did not work for us, and it turned out that the shortest path leads across step 1 (hand-crafting a TGTS). In our case study, the TGG is declarative but not useful, while the TGTS is useful but less declarative.

Hand-crafting a TGTS is more general, but also more low-level than the TGG process of Figure 1. The case study belongs to the range of problems which can be handled with a hand-crafted TGTS but is not suited for applying the TGG approach (Figure 9b). A fundamental assumption underlying TGGs is that transformations are performed symmetrically in both directions. This assumption does not hold in our case study. The region $TGTS \setminus TGG$ is not empty. Improvements from theory may reduce this region further, but more practical case studies are also needed to explore the potentials and limitations of the TGG approach.

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