Incremental Evaluation of Model Queries over EMF Models[*]

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Abstract. Model-driven development tools built on industry standard platforms, such as the Eclipse Modeling Framework (EMF), heavily utilize model queries in model transformation, well-formedness constraint validation and domain-specific model execution. As these queries are executed rather frequently in interactive modeling applications, they have a significant impact on runtime performance and end user experience. However, due to their complexity, these queries can be time consuming to implement and optimize on a case-by-case basis. Consequently, there is a need for a model query framework that combines an easy-to-use and concise declarative query formalism with high runtime performance.

In this paper, we propose a declarative EMF model query framework using the graph pattern formalism as the query specification language. These graph patterns describe the arrangement and properties of model elements that correspond to, e.g. a well-formedness constraint, or an application context of a model transformation rule.

For improved runtime performance, we employ incremental pattern matching techniques: matches of patterns are stored and incrementally maintained upon model manipulation. As a result, query operations can be executed instantly, independently of the complexity of the constraint and the size of the model. We demonstrate our approach in an industrial (AUTOSAR) model validation context and compare it against other solutions.

Keywords: EMF, model query, incremental pattern matching, model validation.

1 Introduction

As model management platforms are gaining more and more industrial attraction, the importance of automated model querying techniques is also increasing. Queries form

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the underpinning of various technologies such as model transformation, code generation, domain specific behaviour simulation and model validation. In their most direct application, model queries may help find violations of well-formedness constraints of a domain-specific modeling language. Query evaluation entails a matching process, where an automated mechanism searches for model elements conforming to the structural pattern and attribute constraints imposed by the given query.

The leading industrial modeling ecosystem, the Eclipse Modeling Framework (EMF [1]), provides different ways to query the contents of models. These approaches range from (1) the use of high-level declarative constraint languages (like OCL [2]) to (2) a dedicated query language [3] resembling SQL, or, in the most basic case, (3) manually programmed model traversal using the generic model manipulation API of EMF. However, industrial experience (including those of the authors) shows scalability problems of complex query evaluation over large EMF models, taken e.g. from the automotive domain. Current practice for improving performance is manual query optimization, which is time consuming to implement on a case-by-case basis.

A promising way to address the performance problem is *incremental pattern matching* (INC) [4]. This technique relies on a *cache* which stores the results of a query explicitly. The result set is readily available from the cache at any time without additional search, and the cache is incrementally updated whenever (elementary or transactional) changes are made to the model. As results are stored, they can be retrieved in constant time, making query evaluation extremely fast. The trade-off is increased memory consumption, and increased update costs (due to continuous cache updates).

In the current paper, we propose EMF-INCQUERY, a framework for defining declarative queries over EMF models, and executing them efficiently *without manual coding*. For the query language, we reuse the concepts of graph patterns (which is a key concept in many graph transformation tools) as a concise and easy way to specify complex structural model queries. High runtime performance is achieved by adapting incremental graph pattern matching techniques.

The benefits of EMF-INCQUERY with respect to the state-of-the-art of querying EMF models include: (i) a significant performance boost when frequently querying complex structural patterns with a moderate amount of modifications in-between, (ii) efficient enumeration of all instances of a class regardless of location, and (iii) simple backwards navigation along references (these latter features address frequently encountered shortcomings of EMF's programming interfaces). We demonstrate the advantages of our approach over existing EMF query alternatives by conducting measurements on a model validation case study in the context of AUTOSAR [5], an industrial standard design platform for automotive embedded systems.

The paper is structured as follows: Section 2 introduces EMF and metamodeling, the mathematical formalism of graph patterns and AUTOSAR. Section 3 presents our declarative approach for queries over EMF. Section 4 elaborates the on-the-fly model validation case study in the domain of AUTOSAR, and Section 5 conducts benchmark measurements to assess the performance. A survey of similar tools and research is presented in Section 6. Finally, Section 7 summarizes the important points of the paper, draws conclusions and plots some future plans.

2 Background

In order to introduce our approach, this section briefly outlines the basics of the Eclipse Modeling Framework, graph patterns and gives a motivating example from the automotive domain based on the AUTOSAR framework.

2.1 Running Example: Constraint Checking in AUTOSAR Models

We demonstrate our model query technique by checking well-formedness constraints over AUTOSAR models. AUTOSAR (short for Automotive Open System Architecture, [5]) is an open and standardized automotive software architecture, jointly developed by automobile manufacturers, suppliers and tool developers. The objectives of the AUTOSAR partnership include the implementation and standardization of basic system functions while providing a highly customizable platform which continues to encourage competition on innovative functions. The common standard should help the integration of functional modules from multiple suppliers and increase scalability to different vehicle and platform variants. It aims to be prepared for the upcoming technologies and to improve cost-efficiency without making any compromise with respect to quality.

To improve quality and reliability of electrical/electronic systems, the validation of AUTOSAR models should be carried out in the early stages of the development process. The standard specifies a multitude of constraints, which should be satisfied to ensure proper functionality in this diverse environment. In this paper, we present three of these constraints, and define validators for each of them.

2.2 EMF and Ecore Metamodeling

The Eclipse Modeling Framework (EMF [1]) provides automated code generation and tooling (e.g. notification, persistence, editor) for Java representation of models. EMF models consist of an (acyclic) containment hierarchy of model elements (*EObjects*) with crossreferences – some of which may only be traversed by programs in one direction (unidirectional references). Additionally, each object has a number of attributes (primitive data values). Models are stored in *EResources* (e.g. files), and interrelated resources are grouped into *EResourceSets*.

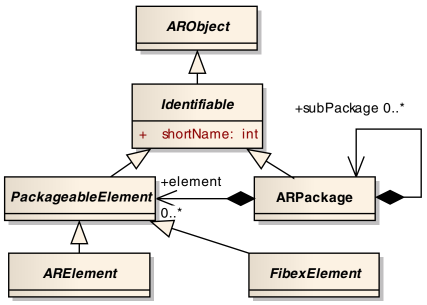


Fig. 1. AUTOSAR metamodel

EMF uses *Ecore* metamodels to describe the abstract syntax of a modeling language. The main elements of Ecore are the following: *EClass* (represented graphically by a rectangle in Fig. 1), *EAttribute* (entries in the rectangle) and *EReference* (depicted as edges). EClasses define the types of EObjects, enumerating EAttributes to specify attribute types of class instances and EReferences to define association types to other EObjects. Some EReferences additionally imply containment (graphically represented by a diamond). Unidirectional references are represented by arrows. Both ends of an association may have a multiplicity constraint attached to them, which declares the number of objects that, at run-time, may participate in an association. The most typical multiplicity constraints are i) the at-most-one (0..1), and (ii) the arbitrary (denoted by *). Inheritance may be defined between classes (depicted by a hollow arrow), which means that the inherited class has all the properties its parent has, and its instances are also instances of the ancestor class, but it may further define some extra features.

These concepts are illustrated by a simplified core part of the AUTOSAR [5] metamodel (Fig. 1). Note that in all metamodel figures of the paper, only relevant attributes are depicted, but no elements are omitted from the inheritance hierarchy. Every object in AUTOSAR inherits from the common ARObject class. If an element has to be identified, it has to inherit from the Identifiable class, and the shortName attribute has to be set. ARElement is a common base class for stand-alone elements, while specializations of FibexElement represent elementary building blocks within the FIBEX package. Instances of ARPackage class are arranged in a strict containment hierarchy by the subPackage association, and every PackageableElement can be aggregated by one of the ARPackages using the element association.

2.3 Graph Patterns

Graph patterns [6] constitute an expressive formalism used for various purposes in Model Driven Development, such as defining declarative model transformation rules, defining the behavioral semantics of dynamic domain specific languages, or capturing general purpose model queries including model validation constraints. A graph pattern (GP) represents conditions (or constraints) that have to be fulfilled by a part of the instance model. A basic graph pattern consists of *structural constraints* prescribing the existence of nodes and edges of a given type (or subtypes, subject to polymorphism). Languages usually include a way to express *attribute constraints*. A *negative application condition* (NAC) defines cases when the original pattern is *not* valid (even if all other constraints are met), in form of a negative sub-pattern. With NACs nested in arbitrary depth, the expressive power of graph patterns is equivalent to first order logic [7]. A match of a graph pattern is a group of model elements that have the exact same configuration as the pattern, satisfying all the constraints (except for NACs, which must be made unsatisfiable).

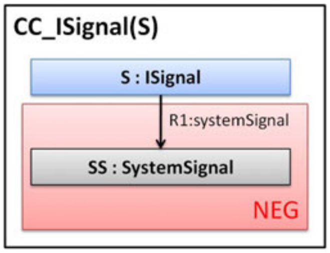


Fig. 2. Graph Pattern for the ISignal consistency check

Fig. 2 depicts a sample graph pattern CC_ISignal. The structural part contains only a single node of type ISignal, but the NAC subpattern connects this node to a SystemSignal instance via an ISignal.systemSignal edge (note that some edges of that type may connect to a SystemSignalGroup instead of a SystemSignal, so the type assertion is relevant). Thus this graph pattern matches ISignal instances that are not connected to a SystemSignal. This graph pattern can be used as a declarative model query, in order to validate the model against a structural well-formedness constraint that requires each ISignal to be connected to a SystemSignal. See Section 4 for further examples.

Model queries with graph patterns. For readers with a strong EMF background, the idea of querying models by specifying graph patterns might not be straightforward. The key step in understanding the concept is that graph patterns declare *what* arrangement of elements is sought after, not *how* or *where* to find them. Each node in the pattern represents an EObject (EMF instance object), and the type of the node identifies the EClass of the object. This feature is useful to select only those model elements that conform to a certain type. Furthermore, the pattern nodes are connected by directed edges, annotated by an EReference type (or *containment*), to express how these elements reference each other. Finally, attribute constraints filtering and comparing the attributes of these elements can also be added.

3 Incremental Pattern Matching over EMF Models

3.1 Benefits

The aim of the EMF-IncQuery approach is to bring the benefits of graph pattern based declarative queries and incremental pattern matching to the EMF domain. The advantage of declarative query specification is that it achieves (efficient) pattern matching without time-consuming, manual coding effort associated to ad-hoc model traversal. While EMF-IncQuery is not the only technology for defining declarative queries over EMF (e.g. EMF Query or MDT-OCL), its distinctive feature is *incremental pattern matching*, with special performance characteristics suitable for scenarios such as on-the-fly well-formedness validation.

Additionally, some shortcomings of EMF are mitigated by the capabilities of EMF-IncQuery, such as cheap enumeration of all instances of a certain type, regardless of where they are located in the resource tree. Another such use is the fast navigation of EReferences in the reverse direction, without having to augment the metamodel with an EOpposite (which is problematic if the metamodel is fixed, or beyond the control of the developer).

3.2 Usage

EMF-IncQuery provides an interface for each declared pattern for (i) retrieving all matches of the pattern, or (ii) retrieving only a restricted set of matches, by binding (a-priori fixing) the value of one or more pattern elements (parameters).

In both cases, the query can be considered instantaneous, since the set of matches of the queried patterns (and certain subpatterns) are automatically cached, and remain available for immediate retrieval throughout the lifetime of the EMF ResourceSet. Even when the EMF model is modified, these caches are continuously and automatically kept up-to-date using the EMF Notification API. This maintenance happens without additional coding, and works regardless how the model was modified (graphical editor, programmatic manipulation, loading a new EMF resource, etc.).

3.3 Algorithm for Incremental Pattern Matching

EMF-IncQuery achieves incremental pattern matching by adapting the RETE algorithm, well-known in the field of rule-based systems (see [4] for our first work on the application of RETE in graph patterns of a model transformation context). The following paragraphs give an overview of the EMF specific behaviour of RETE.

RETE network for graph pattern matching. RETE-based pattern matching relies on a network of nodes storing *partial matches* of a graph pattern. A partial match enumerates those model elements which satisfy a subset of the constraints described by the graph pattern. In a relational database analogy, each node stores a *view*. Partial matches of a pattern are readily available at any time, and they will be incrementally updated whenever model changes occur.

Input nodes serve as the underlying knowledge base representing a model. A RETE input node is introduced for each EClass, to contain the instances of the class (and subclasses), wrapped into unary tuples. The input nodes for EReferences and EAttributes contain all concrete occurrences of the structural feature as binary tuples *(source, target)*. Finally, the EMF notion of containment is also represented by binary tuples in an input node, and usable in pattern definitions.

At each *intermediate node*, *set operations* (e.g. filtering, projection, join, etc.) can be executed on the match sets stored at input nodes to compute the match set which is stored at the intermediate node. Finally, the match set for the entire pattern can be retrieved from the output *production node*. An important kind of intermediate node is the *join node*, which performs a natural join on its parent nodes in terms of relational algebra; whereas a *anti-join node* contains the set of tuples stored at the primary input which do *not* match any tuple from the secondary input.

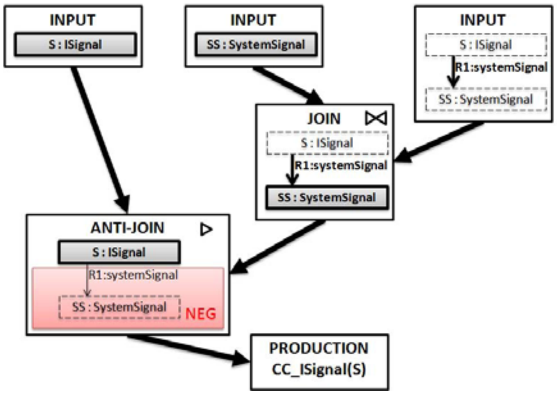


Fig. 3. RETE matcher of CC_ISignal

Fig. 3 shows a simplified RETE network matcher built for the CC_ISignal pattern (see Fig. 2) illustrating the use of join nodes. It uses three input nodes, for instances of EClass ISignal, EClass SystemSignal and EReference ISignal.systemSignal, respectively. The first join node connects the latter two to find ISignal.systemSignal edges that actually end in objects of type SystemSignal. The second intermediate node performs an anti-join of the first input node and the previous join node, therefore containing instances of ISignal that are *not* connected to a SystemSignal via ISignal.systemSignal. This is exactly the match set of pattern CC_ISignal, which is stored in the production node.

Updates after model changes. Upon creation, the RETE net is registered to receive notifications about all changes affecting an EMF ResourceSet, such as creation or deletion of model elements, via a service called EContentAdapter (or similar services provided by a transactional editing domain). Whenever receiving a notification, the input

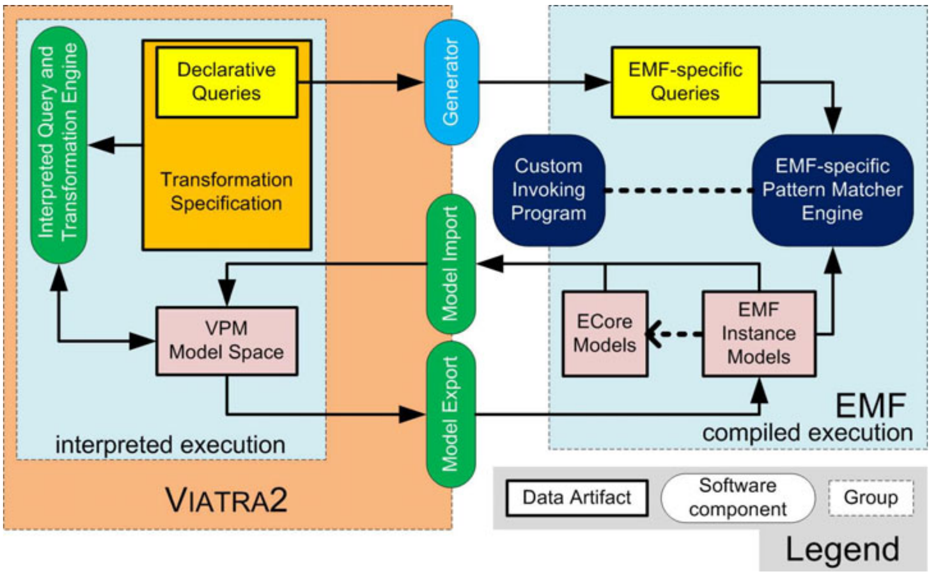


Fig. 4. Overview of the EMF-INCQUERY approach

nodes of RETE are updated. This task is not always trivial: along containment edges, entire subtrees can be attached to an EMF Resource in one step, which requires careful traversal and multiple updates of input nodes.

Each time input nodes receive notifications about an elementary model change, they release an update token on each of their outgoing edges. Such an update token represents changes in the partial matches stored by the RETE node. Positive update tokens reflect newly added tuples, and negative updates refer to tuples being removed from the set. Upon receiving an update token, a RETE node determines how the set of stored tuples will change, and release update tokens of its own to signal these changes to its child nodes. This way, the effects of an update will propagate through the network, eventually influencing the result sets stored in production nodes.

3.4 Architectural Overview of EMF-INCQUERY

Both the query language and the implementation of EMF-INCQUERY are adapted from the model transformation framework VIATRA2 [6]. However, the role of VIATRA2 is limited to the development phase, as the runtime module of EMF-INCQUERY is not dependent on it. Queries in EMF-INCQUERY can be defined by graph patterns in the transformation language [6] of VIATRA2. A *generator component* can be invoked to translate them to the *EMF-specific query* formthat serves as the input for the *EMF-based Pattern Matcher Engine*. The latter is responsible for evaluating queries over EMF ResourceSets, and is intended to be invoked from any Java program.

Graph patterns suitable for the EMF conversion have to refer to the metamodel elements of the relevant EMF format. Therefore VIATRA2 first needs to be aware of the

EMF metamodel (the *Ecore model*), which can be ensured by importing it into VIATRA2's (meta-)model representation, the VPM model space. As an additional benefit, the development of graph pattern based queries can be eased by taking advantage of the VIATRA2 framework. The VIATRA2 transformation interpreter shares identical functional behavior with EMF-INCQUERY. Therefore VIATRA2 serves as a faithful prototyping environment for graph patterns, capable of experimenting on EMF instance models imported into its model space. See Fig. 4 for a graphical overview of the various artifacts, software modules and their relations.

4 Benchmark Case Study

This section presents three well-formedness constraints from the AUTOSAR standard, which form the basis of our measurements in Section 5.

4.1 ISignal Constraint Check

The two metamodel elements for this constraint (SystemSignal and ISignal) are illustrated in Fig. 5, extending Fig. 1. A SystemSignal is the smallest unit of data (it is unique per System) and it is characterized by its length (in bits). (Also two optional elements can be specified, Datatypes and DataPrototype constants, but they are not used in this example.) An ISignal must be created for each SystemSignal (these will be the signals of the Interaction Layer). The graph pattern representation is explained in Section 2.3.

4.2 Signal Group Mapping Constraint Check

Related AUTOSAR elements. The required metamodel elements for this constraint check are illustrated in Fig. 5. A PDU (Protocol data unit) is the smallest information which is delivered through a network layer. It is an abstract element in AUTOSAR, and has multiple different subtypes according to the available network layers. In this case study, we will only examine IPdus (Interaction Layer PDU), and more precisely SignalIPdus. These SignalIPdus used to transfer ISignals. The positions of these ISignals are defined by the ISignalToIPduMappings. The ISignal can be a SystemSignal and a SystemSignalGroup as well. A signal group refers to a set of signals that must always be kept together to ensure the atomic transfer of the information in them.

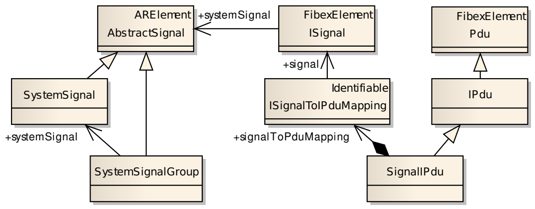
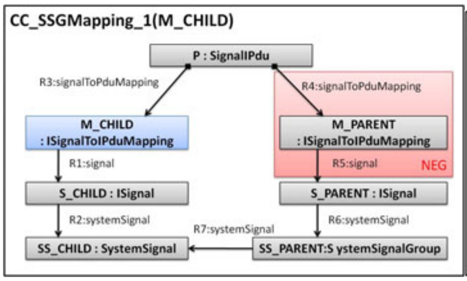
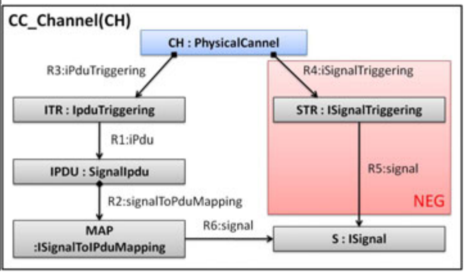


Fig. 5. AUTOSAR metamodel (ISignal)

Constraint check for signal group mapping. To ensure the atomic transfer of a SystemSignalGroup, they have to be packed properly into SignalIPdus. This means that if a SignalGroup is referenced from a SignalIPdu (with an ISignalToIPduMapping), then every Signal in it should be referenced as well from that SignalIPdu (note that an ISignalToIPduMapping references ISignals, but as every SystemSignal and SystemSignalGroup must have an ISignal, this is not a problem – the parent-child relationship is thus expressed between the SystemSignal and SystemSignalGroup instances). This constraint formulated as a graph pattern, matching a possible case of violation where the mapping element corresponding to the SystemSignalGroup is missing (as indicated by the NEG condition), can be seen in Fig. 6(a).



(a) Pattern to find invalid mappings



(b) Pattern to find invalid physical channels

Fig. 6. Consistency check patterns

4.3 Simple PhysicalChannel Consistency Check

Related AUTOSAR elements. To demonstrate the chosen consistency check, some additional AUTOSAR elements have to be described. These elements are illustrated by Fig. 7, extending Fig. 1.

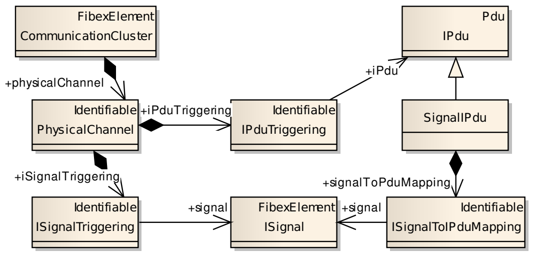


Fig. 7. AUTOSAR metamodel (Channel)

In AUTOSAR, *ECU (Electronic Control Unit)* instances can communicate with each other through a communication medium represented by a PhysicalChannel. Physical Channels are aggregated by a CommunicationCluster, which is the main element to describe the topological connection of communicating ECUs. A Physical Channel can contain ISignalTriggering and IPduTriggering elements. The IPduTriggering and ISignalTriggering describe the usage of IPdus and Signals on physical channels. ISignalTriggering defines the manner of triggering of an ISignal on the channel, on which it is sent. IPduTriggering describes on which channel the IPdu is transmitted.

Consistency check for physical channels. The following constraint has to be satisfied for a physical channel: if a CH PhysicalChannel contains an IPDU SignalIPdu (through an IPduTriggering), then all of the S ISignal, contained by IPDU (through an ISignal-ToIPduMapping), must have a related STR ISignalTriggering in the CH channel. In other words the channel is invalid if there is at least one S ISignal that has no related ISignalTriggering in the channel. This informal definition is formalized in Fig. 6(b) as a form of graph pattern. If the CC_Channel(CH) pattern can be matched for a Physical channel CH, then it is considered to be invalid.

5 Benchmarking and Evaluation

5.1 Generating Sample Models for Benchmarking

For a benchmarking evaluation, we designed a randomized model generator to create sample models of increasing size. For the three constraint cases, we used two different model families: (*A*) for ISignal and SSG and (*B*) for Channel. Both families contain an approximately equal number of valid and invalid model elements. The size of the sample model families ranges from a few thousand elements up to 600.000 (A) and 1.500.000 (B). See the appendix[1] for a detailed description of the generation algorithm.

5.2 Benchmarking

The benchmark simulates the typical scenario of model validation. The user is working with a large model, the modifications are small and local, but the result of the validation needs to be computed as fast as possible. To emulate this, the benchmark sequence consists of the following sequence of operations:

(1) First, the model is *loaded into memory*. In the case of EMF-INCQUERY, most of the overhead is expected to be registered in this phase, as the pattern matching cache needs to be constructed. Note however, that this is a *one-time* penalty, meaning that the cache will be maintained incrementally as long as the model is kept in memory. To highlight this effect, we recorded the times for the loading phase separately.

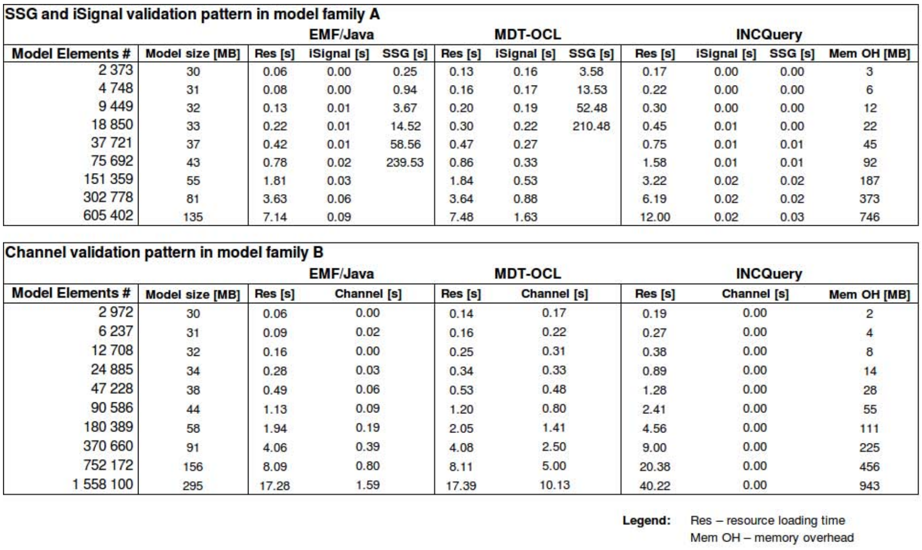
(2) Next, in the *first query phase*, the entire matching set of the constraints is queried. This means that a complete validation is performed on the model, looking for all elements for which the constraint is violated.

(3) After the first query, *model manipulations* are executed. These operations only affect a small fixed subset of elements, and change the constraint's validity (see the appendix[1]).

(4) Finally, in the *second query phase*, the complete validation is performed again, to check the net effect of the manipulation operations on the model.

Benchmark implementations. In addition to our EMF-INCQUERY-based implementation, we created two separate prototypes: a plain Java variant and an OCL variant that uses MDT-OCL [2]. The exact versions of EMF and MDT-OCL were 2.5.0 and 1.2.0 respectively, running on Eclipse Galileo SR1 20090920-1017. We ran the benchmarks

[1] All appendices, along with the complete source code and all test cases can be found at http://viatra.inf.mit.bme.hu/models10



SSG and iSignal validation pattern in model family A

		EMF/Java			MDT-OCL			INCQuery			
Model Elements #	**Model size [MB]**	**Res [s]**	**iSignal [s]**	**SSG [s]**	**Res [s]**	**iSignal [s]**	**SSG [s]**	**Res [s]**	**iSignal [s]**	**SSG [s]**	**Mem OH [MB]**
2 373	30	0.06	0.00	0.25	0.13	0.16	3.58	0.17	0.00	0.00	3
4 748	31	0.08	0.00	0.94	0.16	0.17	13.53	0.22	0.00	0.00	6
9 449	32	0.13	0.01	3.67	0.20	0.19	52.48	0.30	0.00	0.00	12
18 850	33	0.22	0.01	14.52	0.30	0.22	210.48	0.45	0.01	0.00	22
37 721	37	0.42	0.01	58.56	0.47	0.27		0.75	0.01	0.01	45
75 692	43	0.78	0.02	239.53	0.86	0.33		1.58	0.01	0.01	92
151 359	55	1.81	0.03		1.84	0.53		3.22	0.02	0.02	187
302 778	81	3.63	0.06		3.64	0.88		6.19	0.02	0.02	373
605 402	135	7.14	0.09		7.48	1.63		12.00	0.02	0.03	746

Channel validation pattern in model family B

		EMF/Java		MDT-OCL		INCQuery		
Model Elements #	**Model size [MB]**	**Res [s]**	**Channel [s]**	**Res [s]**	**Channel [s]**	**Res [s]**	**Channel [s]**	**Mem OH [MB]**
2 972	30	0.06	0.00	0.14	0.17	0.19	0.00	2
6 237	31	0.09	0.02	0.16	0.22	0.27	0.00	4
12 708	32	0.16	0.00	0.25	0.31	0.38	0.00	8
24 885	34	0.28	0.03	0.34	0.33	0.89	0.00	14
47 228	38	0.49	0.06	0.53	0.48	1.28	0.00	28
90 586	44	1.13	0.09	1.20	0.80	2.41	0.00	55
180 389	58	1.94	0.19	2.05	1.41	4.56	0.00	111
370 660	91	4.06	0.39	4.08	2.50	9.00	0.00	225
752 172	156	8.09	0.80	8.11	5.00	20.38	0.00	456
1 558 100	295	17.28	1.59	17.39	10.13	40.22	0.00	943

Legend: Res – resource loading time
Mem OH – memory overhead

Fig. 8. Results overview

on an Intel Core2 E8400-based PC clocked at 3.00GHz with 3.25GBs of RAM on Windows XP SP3 (32 bit), using the Sun JDK version 1.6.0_17 (with a maximum heap size of 1536 MBs). Execution times were recorded using the java.lang.System class, while memory usage data has been recorded in separate runs using the java.lang.Runtime class (with several garbage collector invocations to minimize the transient effects of Java memory management). The data shown in the results correspond to the averages of 10 runs each.

All implementations share the same code for model manipulation (implementing the specification in the appendix[1]). They differ only in the query phases:

- The EMF-IncQuery variant uses our API for reading the matching set of the graph patterns corresponding to constraints. These operations are only dependent on the size of the graph pattern and the size of the matching set itself (this is empirically confirmed by the results, see Section 5.3). To better reflect memory consumption, the RETE nets for all three constraints were built in each case.
- The plain Java variant performs model traversal using the generated model API of EMF. This approach is not naive, but intuitively manually optimized based on the constraint itself (but *not* on the actual structure of the model [8]).
- The OCL variant has been created by systematically mapping the contents of the graph patterns to OCL concepts, to ensure equivalence. We did not perform any OCL-specific optimization. The exact OCL expressions are in the appendix[1].

To ensure the correctness of the Java implementation, we created a set of small test models and verified the results manually. The rest of the implementations have been checked against the Java variant as the reference, by comparing the number of valid and invalid matches found in each round.

5.3 Analysis of the Results

Based on the results (Fig. 8), we have made the following observations:

(1) As expected, query operations with EMF-INCQUERY are nearly instantaneous, they are only measurable for larger models (where the matching set itself is large). In contrast, both Java and OCL variants exhibit a polynomially increasing characteristic, with respect to model size. The optimized Java implementation outperforms OCL, but only by a constant multiplier.

(2) Although not shown in Fig. 8, the times for model manipulation operations were also measured for all variants, and found to be uniformly negligible. This is expected since very few elements are affected by these operations, therefore the update overhead induced by the RETE network is negligible.

(3) The major overhead of EMF-INCQUERY is registered in the resource loading times (shown in the *Res* column in Fig. 8). It is important to note that the loading times for EMF itself is *included* in the values for EMF-INCQUERY. By looking at the values for loading times and their trends, it can be concluded that EMF-INCQUERY exhibits a linear time increase in both benchmark types, with a factor of approximately 2 compared to the pure EMF implementation. MDT-OCL does not cause a significant increase.

(4) The memory overhead also grows linearly with the model size, but depends on the complexity of the constraint too. More precisely, it depends on the size of the match sets of patterns and that of some sub-patterns depending on the structure of the constructed RETE network. (Actually, the memory overhead is sub-additive with respect to patterns, due to a varying degree of RETE node-sharing.)

It has to be emphasized that in practical operations, the resource loading time increase may not be important as it occurs only once during a model editing session. So, as long as there is enough memory, EMF-INCQUERY provides nearly instantaneous query performance, independently of the complexity of the query and the contents of the model. In certain cases, like for the SSG and ISignal benchmarks, EMF-INCQUERY is the only variant where the query can be executed in the acceptable time range for large models above 500000 elements, even when we take the combined times for resource loading and query execution into consideration. The performance advantage is less apparent for simple queries, as indicated by the figures for the Channel benchmark, where the difference remains in the range of a few seconds even for large models.

Overall, EMF-INCQUERY suits application scenarios with complex queries, which are invoked many times, with relatively small model manipulations in-between. Even though the memory consumption overhead is acceptable even for large models on today's PCs, the optimization techniques (based on combining various pattern matching techniques [8]) previously presented for VIATRA2 apply to EMF-INCQUERY too (even if their implementation will on EMF-level require some future work).

6 Related Work

Model queries over EMF. There are numerous technologies for providing declarative model queries over EMF. Here we give a brief summary of the mainstream techniques, none of which support incremental behavior.

The project EMF Model Query [3] provides query primitives for selecting model elements that satisfy a set of conditions; these conditions range from type and attribute checks to enforcing similar condition checks on model elements reachable through references. The query formalism has several important restrictions: (i) it can only describe tree-like patterns (as opposed to graph patterns); (ii) nodes cannot be captured in variables to be referenced elsewhere in the query; and (iii) the query can only traverse unidirectional relations in their natural direction. Indeed, the expressive power of Model Query is intuitively similar to a formal logic belonging to a class of languages called description logics [9], and weaker than first order logic. Therefore more complex patterns involving circles of references or attribute comparisons between nodes cannot be detected by EMF Model Query without additional coding.

EMF Search [10] is a framework for searching over EMF resources, with controllable scope, several extension facilities, and GUI integration. Unfortunately, only simple textual search (for model element name/label) is available by default; advanced search engines can be provided manually in a metamodel-specific way.

EMF-IncQuery is not the first tool to apply graph pattern based techniques to EMF [11,12], but its incremental pattern matching feature is unique.

Incremental OCL evaluation approaches. OCL [13] is a standardized navigation-based query language, applicable over a range of modeling formalisms. Taking advantage of the expressive features and wide-spread adoption of OCL, the project MDT OCL [2] provides a powerful query interface that evaluates OCL expressions over EMF models. However, backwards navigation along references can still have low performance, and there is no support for incrementality.

Cabot et al. [14] present an advanced three step optimization algorithm for incremental runtime validation of OCL constraints that ensures that constraints are reevaluated only if changes may induce their violation and only on elements that caused this violation. The approach uses promising optimizations, however, it works only on boolean constraints, therefore it is less expressive than our technique.

An interesting model validator over UML models [15] incrementally re-evaluates constraint instances (defined in OCL or by an arbitrary validator program) whenever they are affected by changes. During evaluation of the constraint instance, each model access is recorded, triggering a re-evaluation when the recorded parts are changed. This is also an important weakness: the approach is only applicable in environments where read-only access to the model can be easily recorded, unlike EMF. Additionally, the approach is tailored for model validation, and only permits constraints that have a single free variable; therefore general-purpose model querying is not viable.

Incremental Model Transformation approaches. The model transformation tool TefKat includes an incremental transformation engine [16] that also achieves incremental pattern matching over the factbase-like model representation of the system. The algorithm constructs and preserves a Prolog-like resolution tree for patterns, which is incrementally maintained upon model changes and pattern (rule) changes as well.

As a new effort for the EMF-based model transformation framework ATL [17], incremental transformation execution is supported, including a version of incremental pattern matching that incrementally re-evaluates OCL expressions whose dependencies have been affected by the changes. The approach specifically focuses on transformations, and provides no incremental query interface as of now.

VMTS [18] uses an off-line optimization technique to define (partially) overlapping graph patterns that can share result sets (with caching) during transformation execution. Compared to our approach, it focuses on simple caching of matching result with a small overhead rather than complete caching of patterns.

Giese et al. [19] present a triple graph grammar (TGG) based model synchronization approach, which incrementally updates reference (correspondence) nodes of TGG rules, based on notifications triggered by modified model elements. Their approach share similarities with our RETE based algorithm, in terms of notification observing, however, it does not provide support for explicit querying of (triple) graph patterns.

7 Conclusion and Future Work

In this paper, we presented EMF-INCQUERY as the next evolutionary step in efficiently executing complex queries over EMF models by adapting incremental graph pattern matching technology [4]. It is important to point out that, due to significant differences between EMF and VPM model representation and management - such as unidirectionally navigable graph models stored in multiple files in the case of EMF, vs. bidirectionally navigable graph models with multiple typing stored in a single modelspace in VIATRA2), we could actually reuse only the core concepts of RETE networks from our previous results [4, 8]. In essence, we built an incremental pattern matching solution specific to EMF technology, which is the scope of our paper.

The main lesson we learned from our experiments is that query evaluation should be tailored to the designated application scenario. We have specifically targeted EMF-INCQUERY to support the fast evaluation of complex model queries. Due to the fundamentals of the technology, this works best in the case of interactive applications, where the model modification operations are small (with respect to the size of the entire model). Our results have confirmed the high performance of our implementation, but also the fact that the designer needs to keep the memory impact in mind. Practical applications of this technology include on-the-fly model validation, interactive execution of domain-specific behavior languages, incremental model synchronization, model based monitoring and management, design space exploration and incremental maintenance of (aggregated) model views for development tool environments.

As future work, we intend to work on further automatic optimization, since, as with every declarative query formalism, there is always room for improvement. In the case of our RETE engine, this optimization targets the construction of the cache network, based on the pattern and the contents of the model itself. Additionally, we plan to work on integration with OCL as a query specification language. As it has been shown [20], a significant subsection of OCL can be mapped to the graph pattern formalism, especially if the pattern language is augmented with cardinality expressions.

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