Inference of Design Pattern Instances in UML models via Logic Programming

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Abstract

This paper formalizes the notion of a design model structurally conforming to a design pattern by representing the model as a logic program whilst the pattern as a query. The conformance of a model to a design pattern is equivalent to the satisfaction of the query by the logic program. Harnessing logic inference capability of logic programming languages, we obtain an automated method that infers all the instances of a design pattern in a UML class diagram. We use the Visitor pattern and a price calculation application to demonstrate the technique.

1 Introduction

Design patterns have been an important research subject in the area of software engineering, particularly in reuse-based software engineering since their introduction in computer science [8]. A design pattern describes a proven solution based on the previous experience to a recurring design problem in a reusable form (e.g., see [13]). By reusing high quality solutions, design patterns help the development of systems that are extensible, flexible and maintainable [28].

Evaluation of pattern conformance of designs is concerned with checking valid realizations of a pattern in a design within the context of the application being built. In general, realizing a pattern heavily relies on designer's experience and knowledge of the pattern. Invalid realization of a pattern, however, could deteriorate rather than improve quality of design. Then, a question that naturally arises is "how can one ensure validity of a pattern realization?" The question can be partly addressed by pattern formalization efforts (e.g., see [9, 14, 17, 20, 21, 24, 26, 31]) that facilitate pattern realization (instantiation). For example, template-based approaches (e.g., [31]) formalize patterns in terms of parameters, and a pattern can be instantiated (realized) by stamping out the template. However, in many cases, instantiated pattern realizations often require significant modifications such as adding new elements, modifying or removing some instantiated elements to accommodate application-specific requirements. Since these activities may break pattern conformance and compromise the benefits of using design patterns, pattern conformance must be checked.

There has been much work [2, 4, 5, 7, 10, 15, 16, 27, 30] on identifying pattern instances in code at the programming level where structural properties (e.g., operations, attributes, relationships) of design patterns [13] are searched in code. These works support the reverse engineering efforts at the programming level so as to understand legacy systems and improve their quality attributes. However, there is little work on validating pattern instances at the model level which can greatly improve the quality of design and reduce development cost by finding errors in early development phase. Based on our study, we found that some of the programming-level work (e.g., [7, 16, 27]) can be extended for detecting model-level pattern instances. However, a significant limitation found in these approaches is that pattern specifications are used to represent a typical instance of design pattern and they are used to find exact matching structures in different applications. This limits the applicability of these approaches because in most cases, a design pattern is realized in various forms depending on the application domain, and thus it is very rare to find the same instance in different designs.

To address this issue, we use logic programming to rigorously check pattern conformance of class diagrams described in the Unified Modeling Language (UML) [31]. We represent a design pattern as a query and a class diagram as a logic program. A class diagram is said to conform to a pattern if the logic program representing the class diagram satisfies the query representing the pattern. In this way, we obtain a concise and precise formalisation of the notion of the model conforming to the pattern. This provides a semantic basis for automatic inference of the instances of the pattern in the model. By utilizing inference capability of the logic programming language Prolog, we obtain an automated method that infers all the instances of the pattern in the model.

We base our work on pattern specifications described in the Role-Based Metamodeling Language (RBML) [12, 17]. We chose the RBML because it precisely describes pattern properties and is designed to support model-level use of design patterns for UML models. To demonstrate the technique, we use the Visitor pattern [13] and a model of a price calculation application that calculates the total net price for a composite equipment.

The main contribution of this work is the representation scheme in which a class diagram is represented as logic programs and a pattern as a query. The representation scheme facilitates use of design patterns in software development as follows:

- The scheme can be used to find all instances of the pattern in the model by executing the program for the query. Each answer to the query is an instance of the pattern in the model. Thus, our approach does not simply tell if the model satisfies the pattern but also informs "how" the model satisfies the pattern. Using a debugging technique [29, 23], one can also identify the cause of non-conformence in the model if the query does not have any answer.

- The scheme can be used to validate designer's assignment of pattern roles to model elements. During the development of a software model, the designer may designate certain elements to play particular pattern roles. The scheme can be used to validate this assignment by representing the assignment as an equality constraint and executing the constraint and the query with the program. Furthermore, given a partial mapping of pattern roles and model elements, the scheme can complete the mapping by logic inference.

The remainder of the paper is organized as follows. Section 2 gives an overview of the RBML and Section 3 presents an RBML specification of the Visitor pattern. Section 4 describes how patterns and class diagrams can be represented in Prolog using the Visitor pattern and a price calculation application as examples. Section 5 describes inference of valid pattern instances based on the representation. Section 6 gives an overview of related work, and Section 7 concludes the paper.

2 Role-Based Metamodeling Language (RBML)

The RBML [17] is a UML-based pattern specification language that is designed to support the development of pattern-based UML models. The RBML specifies patterns in terms of roles where a role defines a set of constraints. A role has a base metaclass in the UML metamodel, and is played by instances of the metaclass that satisfy the properties specified in the role [1].

The RBML provides three types of specifications to capture various perspectives of pattern properties [17]: *Static Pattern Specifications* (SPSs), *Interaction Pattern Specifications* (IPSs), and *Statemachine Pattern Specifications* (SMPSs). In this work, we restrict ourselves to SPSs only. An SPS specifies class diagram views of pattern solutions, that is, it characterizes a family of solution class diagrams for a pattern. An SPS consists of *classifier* and *relationship* roles whose bases are *Classifier* and *Relationship* metaclasses in the UML metamodel. A classifier role is associated with a set of feature roles that determines the characteristics of the classifier role and is connected to other classifier roles by relationship roles.

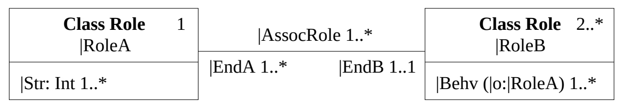


Figure 1. A Static RBML Specification

Fig. 1 shows an example of an SPS. In the SPS, there are two class roles *RoleA* and *RoleB* whose the base is the *Class* metaclass (as denoted above their name), which constrains that only instances of the *Class* metaclass can play the roles. *RoleA* has a structural feature role *Str* whose data type is integer. This further restricts the instances that can play *RoleA* in that they must possess a structural feature with integer data type. *RoleB* has a behavioral feature role *Behv* with a parameter role *o* whose type is *RoleA*. The class roles are connected by association role *AssocRole* that has two association end roles *EndA* and *EndB*. Each role defines a role multiplicity (shown near the role name) constraining the number of elements that can play the role. For example, *RoleA* has *1..** role multiplicity constraining that there can be one or more elements playing the role.

A role is associated with a set of *metamodel-level constraints*. Metamodel-level constraints specialize the UML metamodel by restricting the type of model elements that can play the role. They are represented graphically in diagram or textually in the Object Constraint Language (OCL) [33]. For example, in Fig. 1 *RoleA* has three metamodel-level constraints represented graphically: 1) the base metaclass constraint *Class* requires that a model element playing the *RoleA* role must be a class (an instance of the *Class* metaclass), 2) the structural feature constraint *Str* demands that a model element playing the *RoleA* role must have one

[1] Note that the notion of roles in the RBML is different from the one in the UML in that RBML roles are defined at the metamodel level and played by model elements, while UML roles are defined at the model level and played by objects (for details, see [18])

or more structural features playing the *Str* role, 3) the role multiplicity constraint *1* postulates that there must be exactly one class playing *RoleA*. The SPS also has the following OCL metamodel-level constraints:

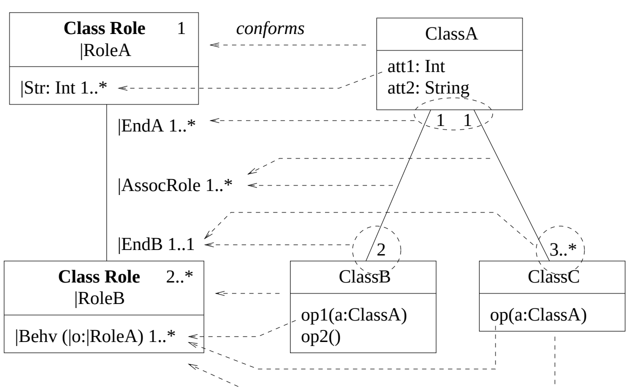
- Classes playing *RoleA* must be concrete:
  context |RoleA **inv**: self.isAbstract = false

- Association ends playing *EndA* must have a multiplicity of *1*:
  context |EndA **inv**: self.lowerBound() = 1 and self.upperBound() = 1

- Association ends playing *EndB* must have a multiplicity in the range of *1..**:
  context |EndA **inv**: self.lowerBound() = 1 and self.upperBound() = *

2.1 Static Pattern Specification Conformance

In this work, we use SPSs of a design pattern to evaluate pattern conformance of a UML class diagram. A class diagram is said to structurally conform to an SPS when the model satisfies the metamodel-level constraints specified in the roles of the SPS. In order for a class diagram to conform to an SPS, the class diagram must posses model elements that can play the roles in the SPS, that is, the model elements must satisfy the constraints defined in the roles.



(a) SPS (b) Class Diagram

Figure 2. Examples of Conforming Class Diagrams

Fig. 2 shows an example of a conforming class diagram to the SPS in Fig. 1. In the example, *ClassA* conforms to the metamodel-level constraints of *RoleA* described above because 1) *ClassA* is an instance of the *Class* metaclass, 2) it has an attribute whose type is integer, and 3) it is the only class in the model that can play the role, 4) it is concrete. *ClassA* may have properties not participating in the pattern (e.g., *att2*). *ClassB* and *ClassC* are described similarly. The two association ends on *ClassA* conform to the metamodel-level constraints of the *EndA* role since a) they both have an object multiplicity of *1*, and b) the number of the association ends playing the role *EndA* is 2, satisfying the role mulitiplicity *1..** of the *EndA* role. Similarly, both the association end on *ClassB* and the association end on *ClassC* satisfy the metamodel-level constraints of the *EndB* role. A noteworthy point is that even though the object multiplicities *2*, *3..**) on these two ends are not exactly same as *1..** as described in the OCL, they satisfy the constraint because they are within the range of *1..**.

3 Visitor Pattern Specification

In this section, we give an example of an SPS for the Visitor pattern [13]. The Visitor pattern provides a solution for handling crosscutting operations in a structure of classes called *elements* by putting these operations into separate classes called *visitors* and having the visitors visit the elements to perform the operations on the elements.

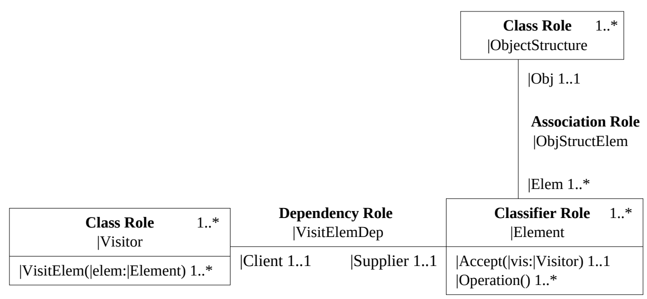


Figure 3. A Partial SPS for the *Visitor* Pattern

Fig. 3 shows a partial SPS of the Visitor pattern. The SPS characterizes class diagrams that have classes playing *Visitor*, *Element*, and *ObjectStructure* roles and relationships playing *VisitElemDep* and *ObjStrucElem* roles. The *Visitor* role specifies that there must be at least one or more classes (denoted by the role multiplicity *1..**) playing the role, and the visitor classes must have one or more behavioral features for visiting elements to carry out necessary operations on the elements. The *Element* role specifies that element classes must have one operation that accepts the visitor and operations to be performed by the visitor. The *ObjectStructure* role specifies that there should be exactly one class playing the role that defines the structure of *Element* objects on which the visitors travel.

The properties (e.g., role multiplicities, base metaclasses) of the SPS shown in the diagram are metamodel-level constraints expressed graphically. Other metamodel-level constraints difficult to express in the diagram are described in the OCL. The following are some of the OCL metamodel-level constraints defined for the Visitor SPS:

- Classifiers that play the *Visitor* role must be concrete classes:
  context |Visitor **inv**: self.isAbstract = false

- Classifiers that play the *ObjectStructure* role must be concrete classes:
  context |ObjectStructure **inv**: self.isAbstract = false

- Dependencies that play the *VisitElemDep* role must be usage dependencies:
  context |VisitElemDep **inv**: self.stereotype.name = "usage"

- An association end playing the *Obj* role must have a multiplicity of 0..1 and not be navigable:
  context |Obj **inv**:
  self.lowerBound() = 0 and self.upperBound() = 1 and self.isNavigable = false

- An association end playing the *Elem* role must have a multiplicity of 1..* and be navigable:
  context |Elem **inv**:
  self.lowerBound() = 1 and self.upperBound() = * and self.isNavigable = true

Note that the Visitor SPS is developed to be partial for simplicity of the demonstration of the technique. A full SPS would include properties constraining that there should be a corresponding *VisitElem* operation for every concrete *Element* classes. To specify this, the SPS should be extended with role hierarchies that involve the notion of abstract and concrete roles (for details, see [18]).

4 Representing Patterns and Models in Prolog

In this and the next sections, we describe how logic programming rigorously evaluates pattern conformance using a model of a price calculation application and the visitor pattern SPS presented in Section 2. The application calculates the total net price of a composite equipment from the net prices of its parts using the Visitor pattern. Fig. 4 show the class diagram.

The diagram describes equipment structures that consist of cards and chassises where a chassis is a composite equipment of cards. A *PricingVisitor* object visits each element in the equipment structure and gets its net price in order to calculate the total net price of the equipment. Operations *visitCard* and *visitChassis* are used to visit *Card* and *Chassis* objects. A visited element accepts the visitor object and

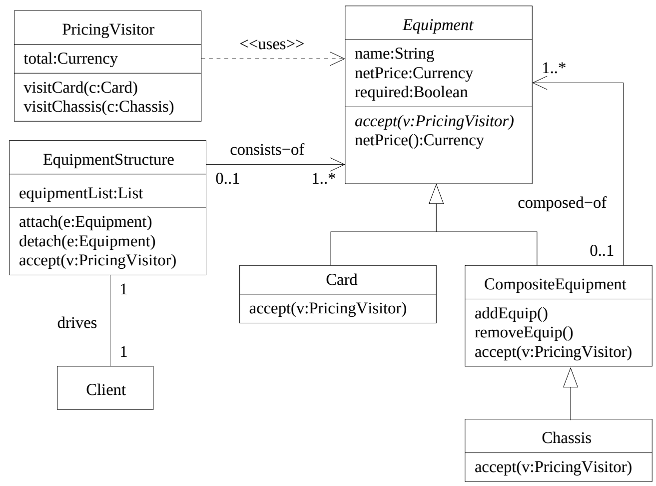


Figure 4. A Class Diagram of a Price Calculation Application

returns itself to the visitor. The visitor then calls the *netPrice* operation to the element to get its net price.

A prerequisite for any automated tool for reasoning about UML design models is a representation scheme for model elements. A logic program is declarative in that it describes what a problem is but not how it can be solved. Solutions to the problem can be generated by a logic programming language system such as Prolog. The domain of the problem is described as a collection of logic statements and so is the problem. Logic inference capability of a logic programming language such as Prolog can not only check if the problem is solvable but also can find all solutions to the problem.

4.1 Models as Logic Programs

This section presents a scheme for representing model elements of a UML class diagrams and its associated OCL constraints as Prolog statements. A class diagram is composed of types and relationships between them. A type is an interface, a class or a classifier while a relationship is a dependency, an association or an inheritance. We will consider only the above types and relationships in this paper. Other kinds of types and relationships can be dealt with similarly.

Kinds of type: These are different kinds of types such as classifiers, classes and interfaces. Each kind corresponds to a unary predicate with the name of the type as its argument. For instance, the *equipment* type is an abstract type, which is represented by the Prolog fact *abstract_class(equipment)*.

The kinds of types in Fig. 4 are represented by the following Prolog facts.

```
abstract_class(equipment).
concrete_class(card).
concrete_class(pricingVisitor).
concrete_class(chassis).
concrete_class(equipmentStructure).
concrete_class(client).
concrete_class(compositeEquipment).
```

Features of type: A type has a number of attributes, operations, association ends and dependency ends (suppliers and clients). These are called features of the type. That a type has a feature is represented as a fact of the form *has_feature(TName, Info)* where *TName* is the name of the type and *Info* is a ground term describing the feature.

Operations and Attributes: That a type has an operation is represented as a Prolog fact *has_feature(TName, op(OpName, ArgTypes, RType))*. *TName* is the name of the type, *OpName* the name of the operation, *ArgTypes* the list of its argument types and *RType* the type of its returned value. For example, the only operation defined in the *chassis* class in Fig. 4 is represented by *has_feature(chassis,op(accept,[pricingVisitor],void))* and the operations defined in the *equipment* class are encoded as these Prolog facts.

```
has_feature(equipment,
            op(accept,[pricingVisitor],void)).
has_feature(equipment,op(netPrice,[],void)).
```

Attributes are treated similarly. That a type has an attribute is represented as a Prolog fact of the form *has_feature(TName,attr(AttrName,AttrType))* where *TName* is the name of the type, *AttrName* the name of the attribute and *AttrType* the type of the attribute. For instance, the attributes of the *equipment* class are encoded as these Prolog facts.

```
has_feature(equipment,attr(name,string)).
has_feature(equipment,attr(netPrice,currency)).
has_feature(equipment,attr(required,boolean)).
```

Association and Dependency: An association has two association ends that may be annotated with object multiplicity and navigability constraints. An association is uniquely identified with its two ends. Thus, an association is represented by representing its ends. An association end of a type is represented by a fact *has_feature(TName,assoc(AssocName, Navigability, bounds(Lower,Upper)))* where *TName* is the name of the type that participates in the association at the end. *AssocName* is the name of the association. *Navigability* is either *true* or *false*, indicating whether the end is navigable. *Lower* is the lower bound on the object multiplicity at the end and *Upper* the upper bound. For instance, the association *composedOf* is represented by these two facts:

```
has_feature(equipment,
    assoc(composedOf,false,bounds(1,many))).
has_feature(compositeEquipment,
    assoc(composedOf,true,bounds(0,1))).
```

Dependency relationships are represented in a similar way as association relationships. A dependency end of a type is represented by a Prolog fact of the form *has_feature(TName,depend(DependName,Navigability))* where *TName* is the name of the type, *DependName* the name of the dependency that the type participates at that end. Navigability at two ends of a dependency is used to indicate the direction of the dependency. The only dependency *uses* in Fig. 4 is represented by these two facts.

```
has_feature(equipment,depend(uses,true)).
has_feature(pricingVisitor,depend(uses,false)).
```

Inheritance: Inheritance relationships induce a subtyping relation between types. The relation is represented by a predicate *is_a* such that *is_a*(T1,T2) indicates that T1 is a sub-type of T2. The sub-typing relation in Fig. 4 is represented as follows.

```
is_a(compositeEquipment,equipment).
is_a(chassis,compositeEquipment).
is_a(card,equipment).
```

Metamodel knowledge The Prolog facts obtained as above are model specific. They are complemented with Prolog rules that represent metamodel knowledge. The set of types of one kind may be contained in the set of types of another kind. The containment relationship between two kinds is represented by a Prolog rule of the form *Kind_1(X) :- Kind_2(X)* where X is a variable, indicating that types of *Kind_2* are also types of *Kind_1*. For instance, that both interfaces and classes are classifiers is encoded by the following Prolog rules.

```
classifier(X) :- interface(X).
classifier(X) :- class(X).
```

and that both concrete and abstract classes are classes is encoded as

```
class(X) :- abstract_class(X).
class(X) :- concrete_class(X).
```

The knowledge that the sub-typing relation is transitive is encoded by this Prolog rule: *is_a(X,Y) :- is_a(X,Z), is_a(Z,Y)*. Since inheritance is non-cyclic, a call to *is_a*/2 with its first argument being a ground term is guaranteed to terminate universally. The translation from patterns to queries ensures that *is_a*/2 is always called with its first argument ground. Sub-typing induces a rule for inherited features:

```
has_feature(T,F) :- is_a(T,T1),has_feature(T1,F).
```

The program that represents the UML model consists of the facts and rules obtained as above and the following rules that realizes the containment relation between pairs of object multiplicity bounds.

```
bounds_subset(bounds(L1,U1),bounds(L2,U2)) :-
    bound_leq(L2,L1),
    bound_leq(U1,U2).

bound_leq(B1,B2) :-
    B2 == many -> true; B1 \== many, B1 =< B2.
```

The predicate *bounds_subset* will only be used to check a given pair of bounds is contained in another given pair of bounds; it will not be used to generate the containment relation between pairs of bounds.

4.2 Patterns as Queries

The goal of inference is to discover a mapping from pattern roles to model elements such that when the roles are substituted by the model elements, the pattern is satisfied by the model. For this purpose, we represent a design pattern as a query. The representation uses the same predicates for representing UML models. Each role is represented as a variable. Roles except association end roles are represented as atoms in the same way as their corresponding model elements are represented as facts. For instance, the three type roles in Fig. 3 is represented as *class(Visitor)*, *class(ObjectStructure)* and *classifier(Element)* respectively. For instance, the dependency end role *Client* is represented *has_feature(Visitor,depend(VisitElemDep,false))* . That class role *Visitor* has an unary behavioral role *VisitElem* with an argument of type *Element* is represented as *has_feature(Visitor,op(VisitElement,[Element],void))*.

Association end roles are represented as follows. First we note that object multiplicity for a relationship end playing a relationship end role and its navigability are written as an OCL constraint. For instance, the association end role *Obj* is constrained by this OCL constraint.

- An association end playing the *Obj* role must have a multiplicity of 0..1 and it is not navigable:
  context |Obj **inv**:
  self.lowerBound()=0 and self.upperBound()=1 and self.isNavigable=false

The association end role *Obj* is represented by these two atoms

```
has_feature(ObjectStructure,
    assoc(ObjStructElem,false,ObjBnds)),
bound_subset(ObjBnds,bounds(0,1))
```

where *ObjBnds* is a variable not appearing elsewhere. The role *Obj* does not appear in this representation since it is uniquely determined by the roles *ObjectStructure* and *ObjStructElem*. In fact, an association end need not be named if it has no attached OCL constraints. Observe that *ObjBnds* is the pair of object multiplicity bounds for the model element that plays the *Obj* role and that *bound_subset(ObjBnds,bounds(0,1))* checks if *ObjBnds* is contained in the pair of object multiplicity bounds for the *Obj* role.

Each pattern role is represented as one or two atoms. The conjunction of the atoms obtained from all pattern roles forms a query. The query representing the example pattern in Fig. 3 is

```
classifier(Element),
has_feature(Element,op(Accept,[Visitor],void)),
has_feature(Element,op(Operation,[],void)),
has_feature(Element,depend(VisitElemDep,true)),
concrete_class(Visitor),
has_feature(Visitor,
            op(VisitElement,[Element],void)),
has_feature(Visitor,depend(VisitElemDep,false)),
concrete_class(ObjectStructure),
has_feature(ObjectStructure,
            assoc(ObjStructElem,false,ObjBnds)),
bounds_subset(ObjBnds,bounds(0,1)), % OCL
has_feature(Element,
            assoc(ObjStructElem,true,ElemBnds)),
bounds_subset(ElemBnds,bounds(1,many)), % OCL
```

5 Inference of Pattern Instances

The logic program represents elements in a UML model and their relationships whilst the query represents roles in a pattern and their relationships. This facilitates inference of instances of a pattern in a model because mappings from roles to model elements can be found by executing the program and query. The inference is realized in two steps as follows. We first compute a superset of the set of valid mappings. Each mapping in the superset is valid except that role multiplicity contraint of pattern roles may be violated. We call such a mapping a candidate mapping. In the second step, invalid candidate mappings are removed from the superset by enforcing realization multiplicity constraints. The following theorem states that the set of all candidate mappings can be obtained by computing all computed answers to the query with the program and projecting the computed answers to the set of the variables that represent roles. In addition, the LD-resolution of the query with the program will always terminate.

Theorem 1 *Let P denotes the program, Q the query and V the set of variables representing roles. Then*

(a) *The LD-resolution of $P \cup \{\leftarrow Q\}$ universally terminates.*

(b) *A substitution θ is a computed answer to $P \cup \{\leftarrow Q\}$ via LD-resolution if and only if $\theta \uparrow V$ is a candidate mapping where $\theta \uparrow V$ is θ restricted to V.*

A proof of the above theorem is put in an appendix for reviewing.

5.1 Enforcing Role Multiplicity

The second step cannot be done by processing candidate mappings individually because two or more candidates may invalidate one another. For instance, if a class role has a role multiplicity constraint 1..1 and there are two candidate mappings in which the role is mapped to two different classes in the model then there is no instance of the pattern in the model. Let $\mathcal{C}_{P,Q}$ be the set of computed answers to $P \cup \{\leftarrow Q\}$ restricted to V. $\mathcal{C}_{P,Q}$ is the set of candidate mappings. Role multiplicity constraints are enforced by removing invalid candidate mappings from $\mathcal{C}_{P,Q}$. Let $\mathcal{X} \uplus \mathcal{Y} = \{X \cup Y \mid X \in \mathcal{X} \wedge Y \in \mathcal{Y}\}$. For the model in Fig. 4 and the pattern in Fig. 3, $\mathcal{C}_{P,Q}$ is

$$\left\{\left\{\begin{array}{l} Accept \mapsto accept, Visitor \mapsto pricingVisitor, \\ VisitElemDep \mapsto uses \end{array}\right\}\right\} \uplus \left\{\begin{array}{l} \left\{\begin{array}{l} ObjectStructure \mapsto equipmentStructure, \\ ObjStructElem \mapsto consistsOf \end{array}\right\}, \\ \left\{\begin{array}{l} ObjectStructure \mapsto compositeEquipment, \\ ObjStructElem \mapsto composedOf \end{array}\right\}, \\ \left\{\begin{array}{l} ObjectStructure \mapsto chassis, \\ ObjStructElem \mapsto composedOf \end{array}\right\} \end{array}\right\} \uplus \left\{\begin{array}{l} \left\{\begin{array}{l} Element \mapsto chassis, VisitElement \mapsto visitChassis, \\ Operation \mapsto addEquip \end{array}\right\}, \\ \left\{\begin{array}{l} Element \mapsto chassis, VisitElement \mapsto visitChassis, \\ Operation \mapsto removeEquip \end{array}\right\}, \\ \left\{\begin{array}{l} Element \mapsto chassis, VisitElement \mapsto visitChassis, \\ Operation \mapsto netPrice \end{array}\right\}, \\ \left\{\begin{array}{l} Element \mapsto card, VisitElement \mapsto visitCard, \\ Operation \mapsto netPrice \end{array}\right\} \end{array}\right\}$$

5.1.1 Feature Role Multiplicity

A role multiplicity constraint L..U on a feature role F of a type role T is satisfied by a subset of the set of candidate mappings if every candidate in the subset maps T into the same type t and the number of the features of t that can play the feature role F is between L and U. This requires grouping candidate mappings around those individual types that can play the type role T. The set of the types that can play the type role T is $\mathcal{C}^{T}_{P,Q} = \{\mu(T) \mid \mu \in \mathcal{C}_{P,Q}\}$. Let $t \in \{\mu(T) \mid \mu \in \mathcal{C}_{P,Q}\}$. The set of candidate mappings that map T to t is $\mathcal{C}^{T,t}_{P,Q} = \{\mu \mid \mu(T) = t \wedge \mu \in \mathcal{C}_{P,Q}\}$. This set satisfies the role multiplicity constraint L..U on the feature role F iff

$$L \leq \|\{\mu(F) \mid \mu \in \mathcal{C}^{T,t}_{P,Q}\}\| \leq U$$

where $\|S\|$ is the cardinality of a set S. Thus, the set of candidate mappings that satisfy the role multiplicity constraint L..U on the feature role F of the type role T is

$$\bigcup\{\mathcal{C}^{T,t}_{P,Q} \mid (t \in \mathcal{C}^{T}_{P,Q}) \wedge (L \leq \|\{\mu(F) \mid \mu \in \mathcal{C}^{T,t}_{P,Q}\}\| \leq U)\}$$

Each feature role multiplicity constraint may remove one or more candidate mappings from $\mathcal{C}_{P,Q}$. The set of remaining candidate mappings is the intersection of the sets of candidate mappings that satisfy individual feature role multiplicity constraints. No mappings is removed from $\mathcal{C}_{P,Q}$ by enforcing feature role multiplicity constraints in Fig. 3.

5.1.2 Type Role Multiplicity

Finally, the remaining candidate mappings are checked to decide if the model conforms to the pattern by satisfying all type role multiplicity constraints. The role multiplicity constraint L..U on a type role T is satisfied iff $L \leq \|\{\mu(T) \mid \mu \in \mathcal{C}_{P,Q}\}\| \leq U$. For instance, we have $\{\mu(Element) \mid \mu \in \mathcal{C}_{P,Q}\} = \{chassis, card\}$ and hence $1 \leq \|\{\mu(Element) \mid \mu \in \mathcal{C}_{P,Q}\}\| \leq many$ holds. Should *Element* have a role multiplicity constraint 1..1, the model would not conform to the pattern since $\|\{\mu(Element) \mid \mu \in \mathcal{C}_{P,Q}\}\| \not\leq 1$. It can be verified that role multiplicity constraints on the other type roles in 3 are also satisfied by $\mathcal{C}_{P,Q}$. Thus, the model in Fig 4 satisfies the pattern in Fig. 3.

6 Related Work

There has been much work on detecting pattern instances in code (e.g., see [2, 5, 10, 15]). Albin-Amiot and Guéhéneuc [2] propose a meta-modeling approach to define and detect design patterns in Java code by structural matching. Balanyi and Ference [5] use a XML-based language to represent design patterns and detect pattern instances in C++ code. Fabry and Mens [10] use logic meta programming to detect design patterns in different languages (e.g., Java, Smalltalk). Heuzeroth *et al.* define design patterns in a tuple of classes, methods, and attributes and use them to find pattern instances in Java code using pattern-specific algorithms. These works support the reverse engineering efforts at the programming level for understanding legacy systems and improving their quality attributes.

The works by Brown [7] and Keller *et al.* [16] use minimal key structures described in the UML as search criteria to identify pattern instances in code. An initial design represented in the UML is extracted from code and searched for the search criteria. Philippow *et al.* [27] extended these approaches by elaborating the search criteria into positive and negative search criteria. While these works are more flexible than the approaches (e.g., see [19, 6]) based on complete matching structures, a drawback remains that the pattern descriptions used are a typical instance of the patterns, and cases are very rare where the same instance is found in models.

Some researchers use metric-based approaches [4, 30]. Antoniol *et al.* [4] use simple class-level metrics (e.g., the number of attributes, the number of operations, the number of different types of relationships) as constraints to recover design patterns in designs. Their approach is similar to the approaches based on minimal key structures in that the structural constraints are expressed in metrics. More sophisticated metrics are used in Shull *et al.*'s work. They define a design pattern by metrics in three categories of object-oriented metrics, structural metrics, and procedural metrics and use them in six steps of a searching algorithm. There is no tool support for their approach, and it is hard to see how the algorithm can be automated.

Similar to our approach, Guennec *et al.* [14] use roles (e.g., classifier roles, feature roles) to define patterns where roles are played by UML model elements. In their work, a UML model is said to conform to a pattern if the names of model elements match to the role names. Using their notion of pattern conformance, it is hard to expect that the elements in a model have the same name as the role name unless the designer is assumed to have knowledge of their pattern specifications and intentionally uses the role names, which is not a valid assumption. Their pattern specifications also have other important properties such as role types and behaviors, but these properties are not considered in the notion of pattern conformance. Our technique establishes a precise notion of pattern conformance and enables rigorous evaluation of pattern conformance without requiring designers to have knowledge of the pattern.

Potential of logic programming as a formal reasoning tool in software engineering has been recognized before [1, 3, 25, 32, 34, 35]. To the best of our knowledge, none of previous works addresses the issue of conformance of a UML model to a given design pattern. Abreu reports a university information system that describes classes, inheritance, attributes and the values used to populate the classes as description logic formulae [1]. The description logic formulae are used to generate more efficient and specific representations for actual use. The emphasis of the work in [1] is to substitute description logic formulae for UML models. Our work focuses on formal reasoning about UML models, in particular, conformance of UML models to design patterns.

Wang *et. al* use constraint logic programming for symbolic execution of requirements described as live sequence charts [32]. Data variables in live sequence charts are represented as logical variables while control variables in live sequence charts as constraints. A truly symbolic execution of live sequence charts is realized by making use of two basic capabilities of a constraint logic programming language: unification and constraint propagation. The work in [32] allows software designer to play with his design whilst our work verifies if his design conforms to a given design pattern and informs him how it conforms to the design pattern.

Zisman and Kozlenkov represent elements in an UML metamodel as axioms and those in an UML model as facts [35]. They use a knowledge base engine based on abduction to discover and analyze structural and behavioral inconsistencies within or between UML specifications. FlowUML [3] uses Horn clauses to specify information flow polices that can be checked against flow information extracted from UML sequence diagrams. These works are mainly concerned with checking consistency within and between UML models. Our work goes beyond that by inferring how a UML model conforms to a given design pattern.

Wuyts proposed a logic meta-programming language SOUL for representing structural relationships in class-based object-oriented systems [34]. A declarative framework based on SOUL was constructed to reason about the structure of Smalltalk programs. SOUL was also used by Mens et. al [25] to manage intentional source code views. A careful study of the representation proposed in [34] reveals that it does not permit inference of design pattern instances in a UML model. For instance, that a class named *c* has a method named *m* is represented as a fact *method(c,m)*. Without information about the types of the arguments and the returned value of the method, precise matching between a method role and a method is not possible.

7 Conclusion

We have presented a rigorous technique for evaluating structural conformance of UML class diagrams to a pattern specification by inferring valid mappings between them using logic programming. We have demonstrated how the technique can be used through the *Visitor* pattern and a model of a price calculation application. The technique can be also used to find instances of domain-specific patterns in a particular domain (e.g., telecommunication, security). We are currently applying the technique to verify valid instances of access control patterns (e.g., RBAC, MAC, DAC) for designs of access control systems in the security domain. The technique can be also used in the area of pattern-based model refactoring [11] for finding applicable design patterns for a given problem model. If the problem model conforms to the problem specification of a pattern, the solution of the pattern can be applied to the model.

In the subsequent work, **we plan to develop tool support for the technique to translate a pattern specification to a query and a UML model into a logic program.** We also plan to extend the technique to include checking semantic conformance of behavioral properties. Examples of such properties are pre- and post-conditions in behavioral features roles and the interactions among pattern elements specified in Interaction Pattern Specifications.

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A Proof for Theorem 5

Proof. Consider (a) first. All calls except those to *bound_subset*/2 universally terminates. Calls to *interface*/1, *class*/1 and *classifier*/1 obviously terminate universally since these predicates are not recursive. Calls to *is_a*/2 universally terminates since sub-typing relations is not cyclic. This together with the fact that all the rules in the program representing the model do not have any function symbol, implies that calls to *has_feature*/2 universally terminates. Note that all facts in the program representing the model are ground, and all variables in the head of a rule also appear in the body of the rule. Therefore, the successful execution of a call to *interface*/1, *class*/1 and *classifier*/1 and *has_feature*/2 grounds all its arguments. By the way of construction, for each call *bound_subset*(Bs1,Bs2) in Q, Bs2 is a ground term and Bs1 occurs in a call that precedes *bound_subset*(Bs1,Bs2), thus, both Bs1 and Bs2 are ground upon the selection of *bound_subset*(Bs1,Bs2) by the LD-resolution, which implies that all computed answers to $P \cup \{\leftarrow Q\}$ are ground substitutions. The set of variables Q consists of those variables representing roles and those variables representing pairs of bounds. Then the proof of (b) follows directly from the soundness and the completeness of the LD-resolution procedure [22].