An Example of Cloning Graph Transformation Rules for Programming

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Abstract

Graphical notations are already popular for the design of software, as witnessed by the success of the Uniform Modeling Languages (UML). In this paper, we advocate the use of graphs and graph transformation for programming graph-based systems. Our case study, the flattening of hierarchical statecharts, reveals that *cloning*, a recently proposed transformation concept, makes graph transformation rules (in the double-pushout approach) more expressive. Thus programming becomes easier, and gets along with simpler control conditions in particular.

Key words: Statecharts, Graph transformation, Clones

1 Introduction

Visual notations have always been popular for designing software, even more since the appearance of the *Unified Modeling Language* (UML), a family of mostly graph-like diagram languages. On the contrary, visual programming with graphs is still far less popular, although graphs are a convenient data structure and the computational model of graph transformation is well developed. We suspect that this is because graph transformation rules alone are not enough. For programming, transformations have to be extended by control conditions (Grace [1]), by control programs (Progres [6]), by control diagrams (Fujaba [3]), or by control predicates (DiaPlan [2], GReAT [5]),

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and control mechanisms force the user to program in a way that is very similar to conventional languages. Graph transformation only simplifies the description of a program's basic operations, but writing down an algorithm that applies these operations in a controlled way is hardly improved by current programming languages based on graph transformation.

This paper tries to improve graph-transformation-based programming by simplifying its control mechanisms. This requires that basic graph transformation steps become more expressive. We are adopting the concept of *cloning* graph transformation rules that has been proposed recently [4]. Cloning allows to express basic program steps with a single transformation rule (scheme) which would otherwise require complicated loops and alternatives. Yet, cloning is a natural approach that does not imply additional efforts to the programmer. This is demonstrated by a case study, the flattening of hierarchical statecharts, i.e., transforming statecharts containing compound states (and-states and or-states) into flat statecharts without them.

The following section briefly introduces the idea of graph transformation with cloning before the problem of flattening statecharts is described in Sect. 3. Sect. 4 shows the proposed approach of applying graph transformation with cloning to solve this problem. The last section concludes the paper.

2 Graph transformation with cloning

This section gives only an informal overview of graph transformation with cloning. Details can be found in [4]. The idea is to specify rule schemes which represent an in general infinite number of rule instances by cloning certain subgraphs. Before describing the rule schemes, we describe the graphs that constitute their left-hand sides and right-hand sides.

A *pattern* is a graph G wherein some nodes are annotated by *cardinality variables*. Each cardinality variable y determines a subgraph G_y which consists of the nodes annotated with y (the *y-fold nodes*), their incident edges, and their adjacent nodes (the *border nodes*). A *y-clone* of pattern G is obtained by binding y to an integer value $k \geq 0$, removing all y-fold nodes and their incident edges from G, and gluing k disjoint copies of G_y to the border nodes. A pattern gets instantiated by binding each cardinality variable to a non-negative integer value and creating y-clones for each variable y. The order in which variables are cloned does not matter as cloning is commutative [4].

A *rule scheme* is a double-pushout rule where left-hand side (lhs), interface, and right-hand side (rhs) are patterns, and which uses pattern morphisms as a straight-forward extension of graph morphisms. Cardinality variables of the rhs have to occur in the lhs also. A rule instance is again a double-pushout rule. A rule is obtained by binding variables of the rhs to the same values as the ones of the lhs and instantiating lhs, interface, and rhs.

As usual, we will omit the interface when drawing a rule scheme, but indicate images of interface nodes by integer numbers. As an example, consider

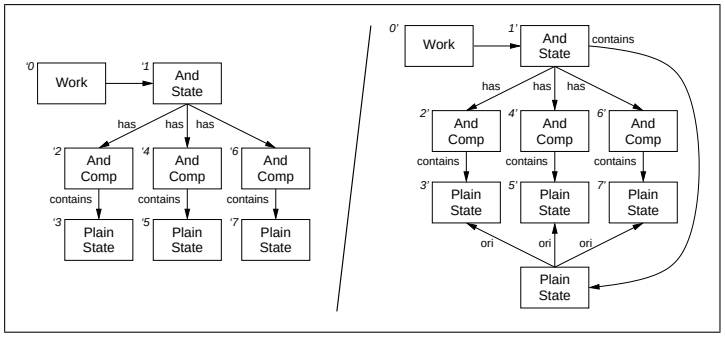
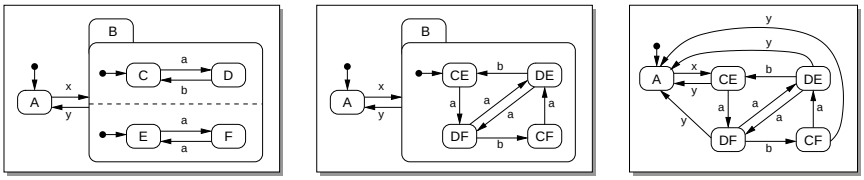


Fig. 1. Rule instance of the rule scheme shown in Fig. 6a with x bound to 3.



(a) (b) (c)

Fig. 2. A statechart diagram with an and-state (a), an equivalent statechart diagram where the and-state has been transformed into an or-state (b), and an equivalent, flat statechart diagram (c).

Fig. 6a which is shown as lhs/rhs. Interface nodes are the ones with the same number, i.e., nodes '1,'2, '3, and '4 of the lhs resp. 1', 2', 3', and 4' of the rhs. The rule scheme is annotated with cardinality variable x. x-fold nodes are visualized as a stack of nodes with an inscribed x. Fig. 1 shows an instance of this rule after creating x-clones with x bound to 3.

3 Statecharts

Statecharts are a visual language for describing behavior; under the name state diagrams, it is one of the graph-like languages of the UML. Statechart diagrams are an extension of finite state machines where transitions are annotated by events, firing conditions, and actions that have to be evaluated when a transition "fires". Hierarchical states can be used to simplify the description of complex behavior. There are two kinds of hierarchical states: An *or-state* contains a complete statechart diagram. When the or-state is active, then one of its contained states is active. Fig. 2b shows a statechart diagram with the or-state B. An *and-state* consists of several and-compartments that are separated by dashed lines. Each compartment contains a complete statechart diagram, like an or-state. When an and-state is active, all statecharts contained in its compartments are active in parallel. Fig. 2a shows a statechart diagram with such an and-state B. In order to fit the description of the flattening algorithm into this paper, we are using simplified statechart diagrams in the following. Simplified statecharts consist of a collection of plain states, and-states, or-states, and initial pseudo states. Initial pseudo states

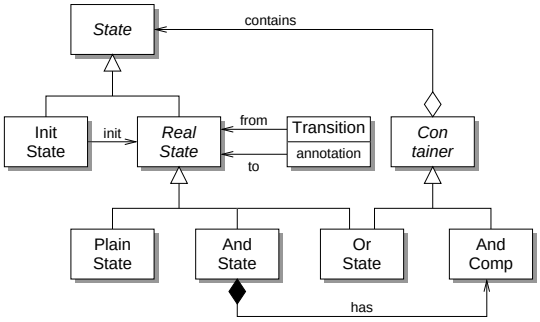


Fig. 3. Metamodel of the considered statechart diagram language.

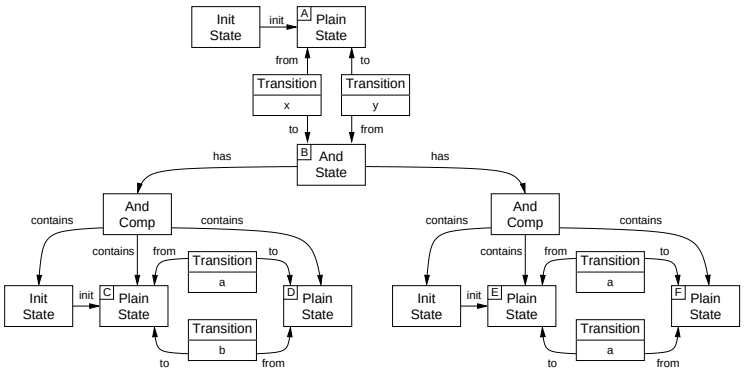


Fig. 4. Graph representation of the statechart diagram in Fig. 2a.

cannot be active; as soon as a statechart is activated, its initial pseudo state is entered and immediately left again via its only and non-annotated transition entering its connected state. Final states and history states are not used here. The annotation of transitions is also simplified: It may consist of events only; firing conditions and actions are not considered here. Also, transitions are not allowed to cross the borders of and-states and or-states. Finally, we simplify handling of conflicting transitions. UML statecharts give transitions firing from higher levels priority over those firing from lower levels. We ignore priorities and assume non-determinism for simplicity.

Fig. 3 defines the metamodel of the considered statechart diagram language as a class diagram. States are either initial pseudo states or real states, i.e., plain states, or-states, or and-states. Or-states are also containers which contain the states of the contained state diagram. And-states consist of and-compartments (*And Comp* in Fig. 3) which are also containers with contained states. Initial pseudo states are associated to their connected state, and transitions are associated to their connected states by *from* and *to* associations. Transitions have an *annotation* attribute that contains the string-valued event for this transition. Based on this metamodel, each statechart diagram can be represented as a graph. Fig. 4 shows the graph representation of the statechart diagram in Fig. 2a.

A transition fires if the state at the transition's source is active and the event is the transition's annotation. If more than one state is active within

an and-state, all outgoing transitions with corresponding annotations fire. An active state whose outgoing transition fires gets inactive, and an inactive state whose incoming transition fires gets active. If an or-state gets active, the state that is connected with the or-state's initial pseudo state gets active, too. For and-states, all of its compartments get active like or-states. Or-states and and-states of our simplified language can be left from any contained state. State B of Fig. 2a, e.g., is left as soon as a y event occurs where any of the contained states C, D, E, or F may be active.

Based on this semantics of transition firing, we can "flatten" a hierarchical statechart diagram by replacing and-states and or-states by equivalent sub-statechart diagrams. Fig. 2 shows this process: All and-states are first replaced by equivalent or-states (b), and finally, all or-states are removed (c).

Replacing an and-state is the more complicated step. The idea of this step is to turn any combination of active contained states into new states. This is similar to building product automata of finite automata. Therefore, we build the cross product of state sets for any and-compartment.[3] In Fig. 2, the contents of and-state B are replaced by the cross product $\{C, D\} \times \{E, F\}$. Transitions are considered next. This step is different from building product automata because a statechart drops an event if the event cannot be consumed by a firing transition. If more than one statechart is active in an and-state, an event can be consumed by some statecharts, but dropped by the others depending on the currently active states and their outgoing transitions. This defines the transitions that have to be created: Let $(s_1, \ldots, s_n)$ be a state from the cross product. If it is active and an event e occurs, there are some and-compartments' statecharts which consume e by a transition $s_i \xrightarrow{e} t_i$, and the other compartments' statecharts drop e, i.e., they stay in their state $s_i = t_i$. Therefore, the equivalent or-state replacing the and-state must contain a transition $(s_1, \ldots, s_n) \xrightarrow{e} (t_1, \ldots, t_n)$. Fig. 2b shows the result.

Removing an or-state is actually simple. As one of the contained state is active iff the or-state is active, we can simply drop the or-state frame, but must take care of the transitions from and to the or-state. Transitions to the or-state are redirected to the contained state that is connected to the or-state's initial pseudo state. And as the or-state can be always left by a transition from the or-state, each transition from the or-state has to be replaced by copies from each of the contained states. Fig. 2c shows the result.

The previous paragraphs have outlined the algorithm of flattening hierarchical statecharts rather coarsely. A precise algorithm in a textual or a common graph-transformation-based language would make use of an abstract representation like the one shown in Fig. 4, and one can imagine that writing it down requires several nested loops and complicated transformations. In the next section, we define the algorithm based on rule schemes that need only a very simple control structure.

[3] This is an expensive operation. A more efficient solution, e.g., is discussed in [7].

```
1  while the graph contains And State or Or State nodes do
2        // remove a bottom level and-state
3        if possible mark_bottom_level_and;
4        for all matches and_create_cross_product;
5        if possible and_create_init;
6        for all matches and_create_trans;
7        as long as possible and_clean_up;
8        // remove all or-states
9        as long as possible or_move_outgoing_trans;
10       as long as possible or_remove
11 done
```

Fig. 5. Control program for flattening statecharts

4 Flattening Statecharts by graph transformation

Sect. 2 introduced rule schemes which shall here be used for specifying the single transformation steps. They have to be combined with a control program in order to present a complete algorithm for flattening hierarchical statecharts. We do not present the control program in some existing language, but use a rather informal notation as we focus on rule schemes and how they make programming with graph transformations easier. Fig. 5 shows this control structure which calls several operations that make use of a single rule scheme. The control program, its constructs, and the rule schemes are explained in the following. Graph transformations require statecharts to be represented as graphs according to the metamodel in Fig. 3.

The control program consists of an outer loop that is repeated as long as there are still hierarchical states. The loop body consists of two parts. The first one (line 3–7) transforms a single and-state which does not contain any hierarchical sub-states (a so-called *bottom level and-state*) into an or-state. This or-state, together with all other or-states, is flattened in the second part (line 9 and 10). This procedure has to be repeated because the graph may contain several and-states, and and-states can be nested, i.e., and-states are flattened from the inside out. The operations follow the overview of the algorithm given in Sect. 3.

Lines 3–7 operate on an and-state that does not contain any hierarchical states. Rule *mark_bottom_level_and* arbitrarily selects one of them by adding a *Work* node [4] to the graph and connecting it with the corresponding *And State* node. Negative application conditions make sure that this and-state does not contain any and- or or-state. This elementary rule is not shown here for space restrictions. The control **if possible** tries to apply rule *mark_bottom_level_and*, but simply continues if the rule fails, i.e., if there is no bottom level and-state.

Fig. 6a shows the rule scheme of the operation *and_create_cross_product*

[4] Please note that the new *Work* node actually violates the metamodel shown in Fig. 3. A possible solution would be relaxing the metamodel while transforming the graph or extending the metamodel accordingly.

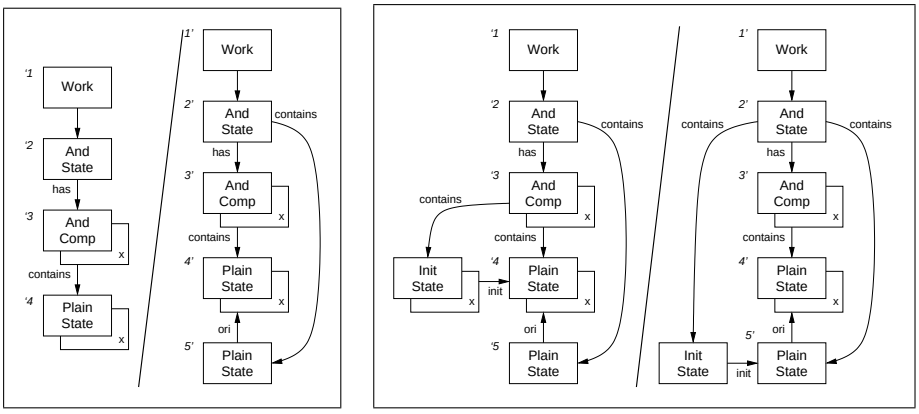
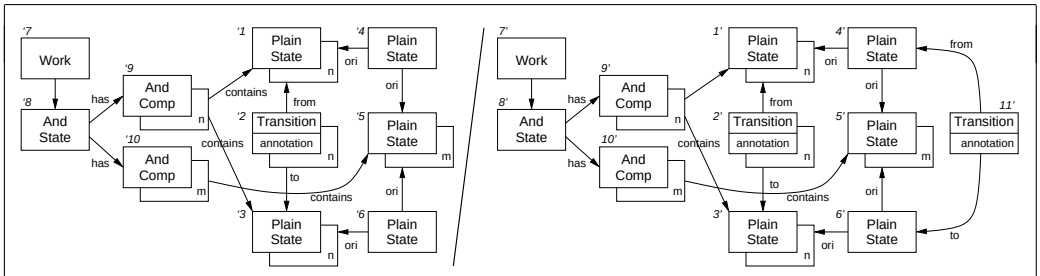


Fig. 6. Rule schemes of operations *and_create_cross_product* (a) and *and_create_init* (b).

that creates the cross product of the state sets of all and-compartments. This rule scheme can be applied to the and-state that has been selected by the previous rule. The idea of the rule scheme is to match an and-state node together with all of its and-compartments and one contained state of each compartment by a rule instantiation. Fig. 1 shows an instance of this rule scheme when binding x to 3, i.e., when the and-state has 3 and-compartments.

By applying the rule instance, a new plain state node 5' is added. Node 5' becomes a new contained node of the and-state (which later will become an or-state by operation *and_clean_up*). Moreover, 5' gets connected by *ori* edges to the original state nodes of the different and-compartments. That way, 5' represents the tuple of state nodes from the different and-compartments. However this requires that cardinality variable x is always bound to the maximum possible value when instantiating the rule. By applying this rule scheme for any possible match for the maximum value being bound to x, this rule scheme creates the complete cross product of the state sets of all and-compartments for the selected and-state. This behavior is specified by the loop control **for all matches**. Please note that this control does not repeat applying the specified rule scheme as long as possible. As the rule scheme's right-hand side contains the left-hand side, this would specify a non-terminating transformation. The loop control rather has to find for the maximum x-value all possible matches and consecutively apply the corresponding rule instance to these matches.

The previous rule instance sets up the cross product of state sets which is the new or-state's set of contained states. However, the initial pseudo state has not yet been created. This is done by operation *and_create_init* (Fig. 6b). Its left-hand side is the same as the right-hand side of the previous rule scheme, but with an additional *Init State* node and with *init* edge. Therefore, the instantiation of the left-hand side, matches the tuple of all initial pseudo states, their connected real states and the new tuple state node that has been created by operation *and_create_cross_product*. The original initial pseudo states



Application condition: card(‘2.annotation) = 1
Priority: $n \prec m$
Action: 11’.annotation := select(‘2.annotation)

Fig. 7. Rule scheme of operation *and_create_trans*

get removed, and a new initial pseudo state gets created. Again, cardinality variable x must be bound to the maximum possible value. The control **if possible** is needed as this rule fails if there is no bottom level and-state.

The next operation has to create transitions between the new states. Fig. 7 shows the corresponding rule scheme. The left-hand side represents two tuple states ‘4 and ‘6 that represent the states ‘1 and ‘5, resp. ‘3 and ‘5. Cloned nodes ‘1 and ‘3 together with ‘2 are those states s_i resp. t_i together with their connecting transition that – as described in Sect. 3 – consume an event by firing the corresponding transitions. As a consequence, this rule scheme has to require as an application condition that the transitions that are matched by the instance of the left-hand side must have the same value of their annotation attribute. [5] Node ‘5 represents the states of those and-compartments that do not consume the corresponding event. Again, cardinality variable n has to be bound to the maximum possible value such that the application condition is satisfied. Afterwards, m has to be bound to the maximum possible value. This requirement is specified by introducing an ordering on the cardinality variables, here $n \prec m$, telling whose value has to be maximized first. When applying an instance of this rule, a new transition is added between the tuple states 4’ and 6’. This new transition has to get the same annotation value as the one of all matched transitions of the left-hand side. The loop control **for all matches** takes care of creating all possible transitions.

The “internals” of the new or-state have been completely created by line 4–6. However, the remaining and-compartments, the original transitions and state nodes as well as the connection edges together with the *Work* node have to be removed. The *And State* node, moreover, has to be replaced by an *Or State* node. This is performed by the operation *and_clean_up* in line 7. *And_clean_up* is actually a set of three straight-forward rule schemes that has been omitted here for space restrictions.

[5] This application condition in Fig. 7 uses *card* as a function that obtains the set cardinality of the multiset of all ‘2.annotation values. The action uses *select* which selects a value from a multiset.

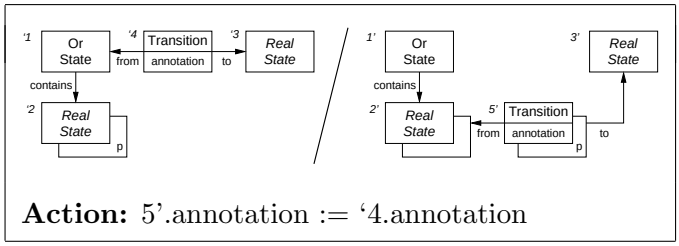


Fig. 8. Rule scheme of operation *or_move_outgoing_trans*

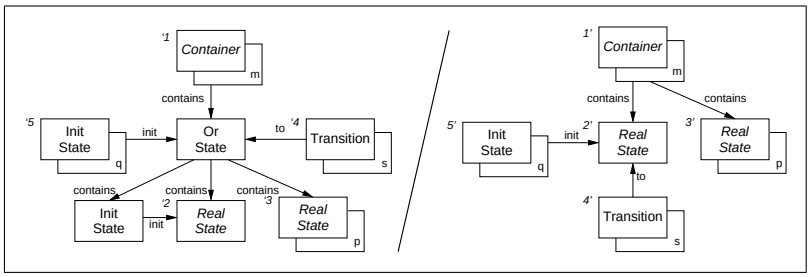


Fig. 9. Rule scheme of operation *or_remove*

The remaining two operations with loop controls (Fig. 5) flatten all or-states of the graph. This applies in particular to the or-state that just has been created from a bottom level and-state. As described in Sect. 3, we have to add copies of transitions leaving an or-state to each of the contained states. This is done by the rule scheme shown in Fig. 8 which is applied with maximum p value to each match of the left-hand side. Please note that as many copies of transition '4 are created as there are states contained in the or-state. All of these new transitions have to get assigned the same annotation values as the match of '4 (c.f. the action in Fig. 8).

Fig. 9 shows the final rule scheme which redirects all incoming transitions to the state that has been connected to the or-state's initial pseudo state, removes this pseudo state and the or-state frame, and uses the containing state – if any – of the previous or-state as the container of the states that have been contained by the or-state. Node '5 with cardinality variable q represents a potential initial pseudo state that has been connected to the or-state. This transition has to be redirected, too.

Please note that the graph does not contain any *Or State* nodes after processing line 10. However, new *Or State* nodes are created in the next loops if there are still *And State* nodes in the graph.

5 Conclusions

In this paper, we have considered the flattening of hierarchical statecharts as a case study for programming based on graph transformation. Space restrictions did only allow to treat simplified statecharts. The missing concepts, like history states, final states, firing conditions, and transition actions as well as enter and exit actions of hierarchical states, can be added in a straight-forward

way. A complete specification will be provided in the future.

The case study revealed that instantiation of rule schemes by cloning makes graph transformation more expressive; it simplifies programming by graph transformation as control programs become simpler. We hope that this concept will support graph transformations to be better accepted for programming tasks in the future.

The expansion of variables to graphs proposed in [4] makes graph transformation still more expressive. But this is beyond the scope of this paper.

Control programs have been presented quite informally in this paper. We are currently combining rule instantiation by cloning with the proposed graph-transformation-based programming language DiaPlan [2] (which already supports variable expansion) and its control structures. This will allow to discuss control structures more thoroughly.

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