

# *On the Abductive or Deductive Nature of Database Schema Validation and Update Processing Problems*

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## **Abstract**

We show that database schema validation and update processing problems such as view updating, materialized view maintenance, integrity constraint checking, integrity constraint maintenance or condition monitoring can be classified as problems of either abductive or deductive nature, according to the reasoning paradigm that inherently suites them. This is done by performing abductive and deductive reasoning on the event rules (Olivé 1991), a set of rules that define the difference between consecutive database states. In this way, we show that it is possible to provide methods able to deal with all these problems as a whole.

We also show how some existing general deductive and abductive procedures may be used to reason on the event rules. In this way, we show that these procedures can deal with all database schema validation and update processing problems considered in this paper.

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## **1 Introduction**

It is largely agreed that databases should contain, at least, base facts, deductive rules (views), integrity constraints and, sometimes, conditions to monitor since these features, together with appropriate reasoning capabilities, facilitate program development and reuse (Grant and Minker 1992). Base facts represent extensional information; while deductive rules, integrity constraints and conditions to monitor represent intentional information, i.e. information that can be inferred from the extensional one. In particular, deductive rules define common knowledge shared by different users; integrity constraints define conditions that each state of the database is required to satisfy and conditions to monitor define information whose changes must be notified to the user.

Database schema validation has become an important problem in database engineering, particularly since databases are able to define intentional information. Schema validation refers to the process of verifying whether a database schema correctly and adequately describes the user's intended needs and requirements

(Adrion, Branstad and Cherniavsky 1982). In general, preventing possible flaws during schema design will prevent those flaws from materializing as execution time errors or inconveniences. Among the typical problems related to database schema validation, we have satisfiability checking, redundancy of integrity constraints, view liveness, etc. (Bry and Manthey 1986, Levy and Sagiv 1995, Decker, Teniente and Urpí 1996).

Databases must also include an update processing system that provides users with a uniform interface through which they can request different kinds of updates, e.g. updates of base facts or updates of derived facts. In the presence of intentional information, updating a database is not a simple task since many issues have to be taken into account (Abiteboul 1988). Therefore, an important amount of research has been devoted to different database updating problems like view updating (Kakas and Mancarella 1990, Guessoum and Lloyd 1990, Teniente and Olivé 1995, Console, Sapino and Dupré 1995, Decker 1996, Lobo and Trajcevski 1997), materialized view maintenance (Gupta and Mumick 1995, Roussopoulos 1998), integrity constraint checking (Sadri and Kowalski 1988, Küchenhoff 1991, Olivé 1991, García, Celma, Mota and Decker 1994, Lee and Ling 1996, Staudt and Jarke 1996), integrity constraint maintenance (Moerkotte and Lockemann 1991, Ceri, Fraternali, Paraboschi and Tanca 1994, Wüthrich 1993, Schewe and Thalheim 1994, Teniente and Olivé 1995) or condition monitoring (Rosenthal, Chakravarthy, Blaustein and Blakeley 1989, Hanson, Chaabouni, Kim and Wang 1990, Qian and Wiederhold 1991, Baralis, Ceri and Paraboschi 1998).

Up to now, the general approach of the research related to database schema validation and update processing has been to provide specific methods for solving particular problems. Therefore, if we were interested in integrating these problems into current database technology, we should incorporate several methods into commercial database management systems. In our opinion, this is one of the main reasons of the difficulty of translating the huge amount of research in this area into practical applications.

Solving these problems requires reasoning about the effect of an update on the database. Therefore, all these methods are either explicitly or implicitly based on a set of rules that define the changes that occur in a transition from an old state of a database to a new one, which is obtained as a result of the application of a certain transaction consisting of a set of base fact updates.

Several authors have argued about the advantages of making explicit the rules that define changes on the database contents induced by the application of a transaction when dealing with database updating problems (Bry 1990, Teniente and Urpí 1995, Denecker and Schreye 1998). These rules allow to guarantee that the updated database is as close as possible to the old database (which is the traditional assumption considered in database updating) and provide a high level of expressiveness since they allow to reason jointly about both states involved in the update (which is specially useful when dealing with database updating problems).

On the other hand, the role of deduction and abduction as reasoning paradigms is widely accepted. For instance, deduction has been used for query processing, while abduction has been applied to fault diagnosis, planning or default reasoning. In the

context of databases, abductive procedures have been proposed for view updating (Bry 1990, Console et al. 1995, Decker 1996) or satisfiability checking (Denecker and Schreye 1998). However, we do not know precisely how many forms of reasoning are necessary for solving known database problems nor, in general, which database problems can be considered of deductive or of abductive nature, according to the reasoning paradigm that is more naturally suited to solve them.

In this paper we show that database schema validation and update processing problems can be classified as either of deductive or of abductive nature. This is done by considering the event rules (Olivé 1991), a particular case of rules that define the exact difference among consecutive database states, and by showing that reasoning deductively or abductively on these rules allows us to naturally specify and handle database problems. As we will see, problems like materialized view maintenance, integrity constraint checking or condition monitoring will be considered as naturally deductive, while problems like view updating, integrity constraint maintenance or enforcing condition activation as naturally abductive.

This first result is an evolution of our work in (Teniente and Urpí 1995) where we proposed two ad-hoc procedures to reason about the event rules that allowed us to classify database updating problems. We extend this work by showing that, in fact, we do not need ad-hoc procedures but that we can consider general reasoning paradigms like deduction and abduction. It follows from this result that general deductive and abductive procedures can be used to reason about the event rules and, hence, to deal with database schema validation and update processing problems.

We also show how some existing general deductive and abductive procedures may be used to reason on the event rules. In this way, we show that these procedures can be used to deal with all database schema validation and update processing problems considered in this paper. This is illustrated by means of examples and we also point out some additional benefits gained by these procedures when reasoning on the event rules. Note that our goal is not that of comparing existing procedures but to show how to use them to reason on the event rules.

Finally, we sketch how the event rules could be used to solve general abductive problems in addition to database schema validation and update processing problems.

Problems related to views, integrity constraints and conditions to be monitored will be encountered whenever we have a database able to deal with intentional information. We have developed our ideas for the particular case of deductive databases due to their clear and precise notation. However, our framework (and, thus, our conclusions) can be easily generalized to all kinds of databases containing views, integrity constraints and conditions like, for instance, relational, active, object or object-relational databases.

This paper is organized as follows. The next section reviews basic concepts of deductive databases. Section 3 shortly presents the concepts of event, transition rules and event rules. Section 4 defines deductive and abductive reasoning on the event rules. Section 5 describes the most important problems related to schema validation and update processing and classifies them as either of deductive or of abductive nature. Section 6 shows how to use general deductive and abductive

procedures to reason on the event rules. Section 7 sketches the use of the event rules to solve general abductive problems. Finally, in section 8 we present our conclusions and point out future work.

## 2 Basic Definitions and Notation

We briefly review the basic concepts of deductive databases (Lloyd 1987, Ullman 1989). We consider a first order language with a universe of constants, a set of variables, a set of predicate names and no function symbols. We will use names beginning with a capital letter for predicate symbols and constants and names beginning with a lower case letter for variables.

A *term* is a variable symbol or a constant symbol. We assume that possible values for terms range over finite domains. If  $P$  is an  $m$ -ary predicate symbol and  $t_1, \dots, t_m$  are terms, then  $P(t_1, \dots, t_m)$  is an *atom*. The atom is *ground* if every  $t_i$  ( $i = 1, \dots, m$ ) is a constant. A *literal* is defined as either an atom or a negated atom.

A *fact* is a formula of the form:  $P(t_1, \dots, t_m) \leftarrow$ , where  $P(t_1, \dots, t_m)$  is a ground atom. We will omit the arrow when denoting an atom.

A *deductive rule* is a formula of the form:  $P(t_1, \dots, t_m) \leftarrow L_1 \wedge \dots \wedge L_n$ , with  $m \geq 0$ ,  $n \geq 1$ , where  $P(t_1, \dots, t_m)$  is an atom denoting the *conclusion* and  $L_1, \dots, L_n$  are literals representing *conditions*.  $P(t_1, \dots, t_m)$  is called the *head* and  $L_1 \wedge \dots \wedge L_n$  the *body* of the deductive rule. Variables in the conclusion or in the conditions are assumed to be universally quantified over the whole formula. The definition of a predicate  $P$  is the set of all rules in the database which have  $P$  in their head. We assume that the terms in the head are distinct variables.

An *integrity constraint* is a formula that every state of the database is required to satisfy. We deal with constraints in *denial* form:  $\leftarrow L_1 \wedge \dots \wedge L_n$ , with  $n \geq 1$ , where the  $L_i$  are literals and all variables are assumed to be universally quantified over the whole formula. We associate to each integrity constraint an inconsistency predicate  $Icn$ , where  $n$  is a positive integer, and thus they have the same form as deductive rules. Then, we would rewrite the former denial as  $Ic1 \leftarrow L_1 \wedge \dots \wedge L_n$ . We call them *integrity rules*. More general constraints can be transformed into denial form by applying the procedure described in (Lloyd and Topor. 1984).

We also assume that the database contains a distinguished derived predicate  $Ic$  defined by the  $n$  clauses:  $Ic \leftarrow Icn$ . That is, one rule for each integrity constraint  $Ici$ ,  $i=1\dots n$ , of the database. Note that  $Ic$  will only hold in those states of the database that violate some integrity constraint and that it will not hold for those states that satisfy all constraints.

A *condition to be monitored* is a formula of the form:  $Cond(t_1, \dots, t_m) \leftarrow L_1 \wedge \dots \wedge L_n$ , with  $m \geq 0$ ,  $n \geq 1$ , where  $Cond(t_1, \dots, t_m)$  is an atom and  $L_1, \dots, L_n$  are literals. Moreover, variables in  $Cond$  and in  $L_1, \dots, L_n$  are assumed to be universally quantified over the whole formula. Each condition to be monitored corresponds to a derived predicate for which certain changes have to be notified to the database user.

A *deductive database*  $D$  is a tuple  $D = (EDB, IDB)$  where  $EDB$  is a set of facts, and  $IDB = DR \cup IC \cup Cond$  is a set of rules such that  $DR$  is a set of deductive

rules, IC a set of integrity rules and Cond a set of conditions to be monitored. The set EDB of facts is called the *extensional* part of the deductive database and the set IDB of rules is called the *intentional* part. We say that a deductive database is consistent if predicate Ic does not hold on it, i.e. if no integrity constraint is violated.

We assume that deductive database predicates are partitioned into base and derived (view) predicates. A base predicate appears only in the extensional part and (possibly) in the body of deductive rules. A derived predicate appears only in the intentional part. Base and derived facts correspond to facts about base and derived predicates, respectively.

As usual, we require that the deductive database before and after any updates is *allowed*, that is, any variable that occurs in a deductive rule, integrity rule or condition to be monitored has an occurrence in a positive literal of the body of the rule. In this paper, we deal with hierarchical<sup>1</sup> databases. Note that, in particular, this kind of databases does not allow to express recursive rules.

### 3 The Event Rules

Intuitively, a database is a dynamic system that changes over time. Changes are effected by EDB updates. These updates define a transition from an old state of the database to a new updated one. In this sense, schema validation and update processing problems can be viewed as database state transition problems. It is possible to define a set of rules that explicitly defines the possible transitions in terms of the difference between consecutive database states. Reasoning about these rules will allow to reason jointly about both states involved in the transition and, thus, to reason about the effect of the updates.

The event rules explicitly define the difference between two consecutive database states. In the following, we shortly review the concepts and terminology of event rules, as presented in (Olivé 1991), and we discuss on the possible use of other sets of rules instead of the event rules.

#### 3.1 Events

Let  $D^o$  be a deductive database,  $T$  a transaction and  $D^n$  the updated deductive database. We say that  $T$  induces a transition from  $D^o$  (the old state) to  $D^n$  (the new state). We assume for the moment that  $T$  consists of an unspecified set of base facts to be inserted and/or deleted.

Due to the deductive rules,  $T$  may induce other updates on some derived predicates. Let  $P$  be one of such predicates, and let  $P^o$  and  $P^n$  denote the same predicate evaluated in  $D^o$  and  $D^n$ , respectively. Assuming that a fact  $P^o(\mathbf{C})$  holds in  $D^o$ , where  $\mathbf{C}$  is a vector of constants, two cases are possible:

<sup>1</sup> Equivalent to nr-datalog- $\neg$  rules, and with the same expressive power as the relational calculus (Abiteboul, Hull and Vianu 1995).

- a.1.  $P^n(\mathbf{C})$  also holds in  $D^n$ .
- a.2.  $P^n(\mathbf{C})$  does not hold in  $D^n$ .

and assuming that  $P^n(\mathbf{C})$  holds in  $D^n$ , two cases are also possible:

- b.1.  $P^o(\mathbf{C})$  also holds in  $D^o$ .
- b.2.  $P^o(\mathbf{C})$  does not hold in  $D^o$ .

In case a.2 we say that a deletion event occurs in the transition, and we denote it by  $\delta P(\mathbf{C})$ . In case b.2 we say that an insertion event occurs in the transition, and we denote it by  $\iota P(\mathbf{C})$ .

Formally, we associate to each predicate  $P$  an *insertion event predicate*  $\iota P$  and a *deletion event predicate*  $\delta P$ , defined as:

- (1)  $\forall \mathbf{x} (\iota P(\mathbf{x}) \leftrightarrow P^n(\mathbf{x}) \wedge \neg P^o(\mathbf{x}))$
- (2)  $\forall \mathbf{x} (\delta P(\mathbf{x}) \leftrightarrow P^o(\mathbf{x}) \wedge \neg P^n(\mathbf{x}))$

where  $\mathbf{x}$  is a vector of variables. From the above, we then have the equivalencies:

- (3)  $\forall \mathbf{x} (P^n(\mathbf{x}) \leftrightarrow (P^o(\mathbf{x}) \wedge \neg \delta P(\mathbf{x})) \vee \iota P(\mathbf{x}))$
- (4)  $\forall \mathbf{x} (\neg P^n(\mathbf{x}) \leftrightarrow (\neg P^o(\mathbf{x}) \wedge \neg \iota P(\mathbf{x})) \vee \delta P(\mathbf{x}))$

We say that an event  $\iota P$  or  $\delta P$  is a base event if  $P$  is a base predicate. Otherwise, it is a derived event. If  $P$  is a base predicate, then  $\iota P$  and  $\delta P$  facts represent insertions and deletions of base facts, respectively. Therefore, we assume from now on that a transaction  $T$  consists of an unspecified set of insertion and/or deletion base event facts. If  $P$  is a derived predicate, an integrity constraint or a condition to be monitored,  $\iota P$  and  $\delta P$  facts represent induced insertions and induced deletions on  $P$ , respectively.

### 3.2 Transition Rules

Let us consider a derived predicate  $P$  of the database. The definition of  $P$  consists of the rules in the deductive database having  $P$  in the conclusion. Assume that there are  $m$  ( $m \geq 1$ ) such rules. For notation's sake, we rename predicate symbols in the conclusions of the  $m$  rules by  $P_1, \dots, P_m$ , replace the implication by an equivalence and add the set of rules:

$$(5) P \leftarrow P_i \quad i = 1 \dots m$$

i.e. one rule defining  $P$  for each derived predicate  $P_i, i = 1 \dots m$ .

Consider now one of the rules  $P_i(\mathbf{x}) \leftrightarrow L_1 \wedge \dots \wedge L_n$ . When this rule is to be evaluated in the new state, its form is  $P_i^n(\mathbf{x}) \leftrightarrow L_1^n \wedge \dots \wedge L_n^n$ , where  $L_j^n$  ( $j = 1 \dots n$ ) is obtained by replacing the predicate  $Q$  of  $L_j$  by  $Q^n$ . Then, if we replace each literal in the body by its equivalent expression given in (3) or (4) we get a new rule which defines the new state predicate  $P_i^n$  in terms of old state predicates and events.

More precisely, if  $L_j^n$  is a positive literal  $Q_j^n(\mathbf{x}_j)$  we apply (3) and replace it by:

$$(Q_j^o(\mathbf{x}_j) \wedge \neg \delta Q_j(\mathbf{x}_j)) \vee \iota Q_j(\mathbf{x}_j)$$

and if  $L_j^n$  is a negative literal  $\neg Q_j^n(\mathbf{x}_j)$  we apply (4) and replace it by:

$$(\neg Q_j^o(\mathbf{x}_j) \wedge \neg \iota Q_j(\mathbf{x}_j)) \vee \delta Q_j(\mathbf{x}_j)$$

After distributing  $\wedge$  over  $\vee$ , we get the set of *transition rules* for  $P_i^n$ . Notice that there are  $2^{k_i}$  such rules (where  $k_i$  is the number of literals in the  $P_i^n$  rule) and that literals in each rule can be of three types: old database literals, base event literals and derived event literals.

#### Example 1

Consider the rule  $\text{Cont}_1(\mathbf{x}) \leftrightarrow \text{Sign}(\mathbf{x}) \wedge \neg \text{Fail-ex}(\mathbf{x})$  stating that contracted people are those who signed an agreement and did not failed the exam. In the new state, this rule has the form  $\text{Cont}_1^n(\mathbf{x}) \leftrightarrow \text{Sign}^n(\mathbf{x}) \wedge \neg \text{Fail-ex}^n(\mathbf{x})$ . Then, replacing  $\text{Sign}^n(\mathbf{x})$  and  $\neg \text{Fail-ex}^n(\mathbf{x})$  by their equivalent expressions given by (3) and (4) we get:

$$\begin{aligned} \text{Cont}_1^n(x) \leftrightarrow & [(Sign^o(x) \wedge \neg \delta Sign(x)) \vee \iota Sign(x)] \wedge \\ & [(\neg Fail-ex^o(x) \wedge \neg \iota Fail-ex(x)) \vee \delta Fail-ex(x)] \end{aligned}$$

and, after distributing  $\wedge$  over  $\vee$ , we get the following transition rules:

$$\begin{aligned} \text{Cont}_1^n(x) \leftarrow & Sign^o(x) \wedge \neg \delta Sign(x) \wedge \neg Fail-ex^o(x) \wedge \neg \iota Fail-ex(x) \\ \text{Cont}_1^n(x) \leftarrow & Sign^o(x) \wedge \neg \delta Sign(x) \wedge \delta Fail-ex(x) \\ \text{Cont}_1^n(x) \leftarrow & \iota Sign(x) \wedge \neg Fail-ex^o(x) \wedge \neg \iota Fail-ex(x) \\ \text{Cont}_1^n(x) \leftarrow & \iota Sign(x) \wedge \delta Fail-ex(x) \end{aligned}$$

Intuitively, it is not difficult to see that the first rule states that  $\text{Cont}(X)$  will be true in the new state of the database if  $\text{Sign}(X)$  was true in the old state,  $\text{Fail-ex}(X)$  was false in the old state and no change of  $\text{Sign}(X)$  and  $\text{Fail-ex}(X)$  is given by the transition. In a similar way, the second rule states that  $\text{Cont}(X)$  will be true in the new state if  $\text{Sign}(X)$  was true and it has not been deleted and if  $\text{Fail-ex}(X)$  has been deleted during the transition. A similar, intuitive, interpretation can be given for the third and forth rules.

For simplicity of presentation, we will omit the subscript when a predicate  $P$  is defined by only one rule and we will omit the superscript<sup>*o*</sup> for denoting old database predicates.

### 3.3 Insertion and Deletion Event Rules

Let  $P$  be a derived predicate. Insertion and deletion event rules of predicate  $P$  are defined respectively as:

$$\begin{aligned} (6) \quad \iota P(\mathbf{x}) & \leftarrow P^n(\mathbf{x}) \wedge \neg P^o(\mathbf{x}) \\ (7) \quad \delta P(\mathbf{x}) & \leftarrow P^o(\mathbf{x}) \wedge \neg P^n(\mathbf{x}) \end{aligned}$$

where  $P$  refers to the current (old) database state and  $P^n$  refers to the transition rule of  $P$ . These event rules define the induced changes that happen in a transition from an old state of a database to a new, updated state. Note that they depend only on the rules of the database, being independent of the stored facts and of any particular transaction.

We would like to point out that these rules can be intensively simplified, as described in (Olivé 1991, Urpí and Olivé 1992, Urpí and Olivé 1994). By simplifying the event rules we obtain a set of semantically equivalent rules, but with a lower evaluation cost. The automatic generation and simplification of the event rules has been implemented in a SunOS environment by means of Quintus Prolog. In this paper, we will consider the simplified version of the event rules.

*Definition 1*

Let  $D = (EDB, IDB)$  be a deductive database. The *augmented database* associated to  $D$  is the tuple  $A(D) = (EDB, IDB^*)$ , where  $IDB^*$  contains the rules in  $DR \cup IC \cup Cond$  and their associated simplified transition and event rules.

*Example 2*

Given the following database  $D = (EDB, IDB)$ :

Sign(John)  
Fail-ex(John)  
 $Cont(x) \leftarrow Sign(x) \wedge \neg Fail-ex(x)$

the corresponding augmented database  $A(D)$  is the following:

Sign(John)  
Fail-ex(John)  
 $Cont(x) \leftarrow Sign(x) \wedge \neg Fail-ex(x)$   
 $\iota Cont(x) \leftarrow Sign(x) \wedge \neg \delta Sign(x) \wedge \delta Fail-ex(x)$   
 $\iota Cont(x) \leftarrow \iota Sign(x) \wedge \neg Fail-ex(x) \wedge \neg \iota Fail-ex(x)$   
 $\iota Cont(x) \leftarrow \iota Sign(x) \wedge \delta Fail-ex(x)$   
 $\delta Cont(x) \leftarrow Cont(x) \wedge \iota Fail-ex(x)$   
 $\delta Cont(x) \leftarrow \delta Cont(x) \wedge \neg Fail-ex(x)$

### 3.4 Using other Rules Instead of the Event Rules

We will use the event rules to provide the basis of our framework for specifying and handling schema validation and update processing problems. However, since our framework is only based on the definition of event given in (1) and (2) (see Section 3.1), we could use any set of rules that defines the difference between consecutive states of the database, instead of the event rules, provided that they preserve the event definition. In this section we show two different sets of rules that could had been used also.

Assume that we have the following deductive rules:

$P(x) \leftarrow Q(x) \wedge R(x)$   
 $R(x) \leftarrow S(x)$

If we simply consider the definition of transition and event rules without applying any simplification, we would have:

$\iota P(x) \leftarrow P^n(x) \wedge \neg P(x)$   
 $\iota R(x) \leftarrow R^n(x) \wedge \neg R(x)$



$$\begin{aligned}
\delta R(x) &\leftarrow R(x) \wedge \neg R^n(x) \\
P^n(x) &\leftarrow Q(x) \wedge \neg \delta Q(x) \wedge R(x) \wedge \neg \delta R(x) \\
P^n(x) &\leftarrow Q(x) \wedge \neg \delta Q(x) \wedge \iota R(x) \\
P^n(x) &\leftarrow \iota Q(x) \wedge R(x) \wedge \neg \delta R(x) \\
P^n(x) &\leftarrow \iota Q(x) \wedge \iota R(x) \\
R^n(x) &\leftarrow S(x) \wedge \neg \delta S(x) \\
R^n(x) &\leftarrow \iota S(x)
\end{aligned}$$

On the other hand, by adapting the rules generated by Küchenhoff (Küchenhoff 1991) to our terminology, we would obtain:

$$\begin{aligned}
\iota P(x) &\leftarrow Q(x) \wedge \neg \delta Q(x) \wedge \iota R(x) \wedge \neg P(x) \\
\iota P(x) &\leftarrow \iota Q(x) \wedge R(x) \wedge \neg \delta R(x) \wedge \neg P(x) \\
\iota P(x) &\leftarrow \iota Q(x) \wedge \iota R(x) \wedge \neg P(x) \\
\iota R(x) &\leftarrow \iota S(x) \\
\delta R(x) &\leftarrow \delta S(x)
\end{aligned}$$

Note that Küchenhoff's rules provide some simplifications with regards to the non-simplified event rules. For instance, insertion event rules about  $R$  do not check that  $R$  was false in the old state of the database. A similar simplification is given for deletion event rules about  $R$ . However, no simplification is applied for the rules defining events on  $P$ .

Finally, the simplified insertion event rules for  $P$  according to (Urpí and Olivé 1992) are the following:

$$\begin{aligned}
\iota P(x) &\leftarrow Q(x) \wedge \neg \delta Q(x) \wedge \iota R(x) \\
\iota P(x) &\leftarrow \iota Q(x) \wedge R(x) \wedge \neg \delta R(x) \\
\iota P(x) &\leftarrow \iota Q(x) \wedge \iota R(x) \\
\iota R(x) &\leftarrow \iota S(x) \\
\delta R(x) &\leftarrow \delta S(x)
\end{aligned}$$

Note that, in addition to the simplifications already provided by Küchenhoff, these rules include also simplifications involving the event rules for  $P$ .

It is not difficult to see that the three sets of rules are semantically equivalent and define the same transitions between consecutive database states. The event definition is preserved in all cases. The only difference relies on the kind of optimizations that have been considered. In fact, we could also think about other sets of rules that incorporate additional optimizations (see for instance (Urpí and Olivé 1994) which incorporates the knowledge provided by the integrity constraints into such set of rules). The differences among possible sets of rules imply advantages or inconveniences as far as efficiency is concerned, but not regarding the ability of solving the problems we deal with in this paper. Thus, our framework does not depend on any particular set of rules.

#### 4 Reasoning on the Event Rules

There is a big amount of problems related to database schema validation and to update processing. Unfortunately, the general approach considered by previous re-

search in this area has been to deal with each problem in an isolated way. So, it is unusual to find a method able to handle several of the previous problems. This limitation can be overcome by considering a set of rules that explicitly define the difference between two consecutive database states and by performing deductive and abductive reasoning on these rules.

The role of deduction and abduction as reasoning paradigms is widely accepted. *Deduction* is an analytic process based on the application of general rules to particular cases, with the inference of a result. *Abduction* is another form of synthetic reasoning which infers the case from the rule and the result.

The event rules define the exact changes, either on base as on derived predicates, produced as a consequence of the application of a given transaction to a database state. Deductive and abductive reasoning can be performed on those rules. As we will see, performing deductive reasoning on the event rules defines changes on derived predicates induced by changes on base predicates. On the other hand, performing abductive reasoning on the event rules defines changes on base predicates needed to satisfy changes on derived predicates. In this way, reasoning deductively or abductively on the event rules provides the basis for solving database schema validation and update processing problems in a uniform way.

In fact, as stated in Section 3.4, any set of rules that precisely defines the difference between consecutive database states could also be used. Due to our previous experience with the event rules, we have considered them in this paper.

#### 4.1 Reasoning Deductively on the Event Rules

Deduction is concerned with inferring consequences from facts via deductive rules. For instance, given a deductive rule  $P(x) \leftarrow Q(x)$  and a fact  $Q(A)$ , deduction infers  $P(A)$  as a consequence of  $Q(A)$ . Thus, deductive reasoning is suitable among other things for finding correct answers to queries.

##### Definition 2

Let  $D = (EDB, IDB)$  be a deductive database and  $G$  a goal  $L_1 \wedge \dots \wedge L_n$ . A *correct answer* to  $G$  over  $EDB$  is a substitution  $\theta$  for variables of  $G$  such that  $G\theta$  is a logical consequence of  $EDB \cup IDB$ , i.e.  $EDB \cup IDB \models G\theta$ .

Since event rules define the changes that occur in a transition from an old state of a database to a new one as a consequence of the application of a given transaction, by considering deduction in the context of the augmented database we can also define how to reason deductively on the event rules.

##### Definition 3

Let  $D = (EDB, IDB)$  be a deductive database,  $A(D) = (EDB, IDB^*)$  its corresponding augmented database,  $T$  a transaction consisting of a set of ground base event facts,  $u$  a derived event. The *deduced consequences on  $u$*  due to the application of  $T$  is the set  $\theta$  of correct answers to  $EDB \cup IDB^* \cup T \cup u$ . Note that each correct answer  $\theta_i \in \theta$  defines a ground derived event  $u\theta_i$  induced as a consequence of the application of  $T$ .

Thus, reasoning deductively on the event rules defines changes on derived predicates induced by changes on base predicates, since  $\theta$  defines all ground facts about  $u$  induced by the application of  $T$  to the current state of the database.

As an example, given the database of Example 2 and the transaction  $T = \{\delta\text{Fail-ex}(\text{John})\}$ , it is not difficult to see that reasoning deductively on the event rules allows to deduce that  $T$  induces  $\iota\text{Cont}(\text{John})$ , i.e.  $\theta = \{x = \text{John}\}$ .

#### 4.2 Reasoning Abductively on the Event Rules

Abduction is aimed at looking for hypothesis that explain a given observation, according to known laws usually specified by means of deductive rules. Abduction (in the absence of integrity constraints) is traditionally defined as follows: Given a set of sentences  $T$  (a theory presentation) and a sentence  $G$  (observation), the abductive task consists of finding a set of sentences  $\Delta$  (abductive explanation for  $G$ ) such that:

$$(1) T \cup \Delta \models G$$

It is usually considered that  $\Delta$  consists of atoms drawn from predicates explicitly indicated as abducible (those whose instances can be assumed when required). Therefore, an *abductive framework* is a pair  $\prec T, Ab \succ$ , where  $Ab$  is the set of abducible predicates, i.e.  $\Delta \subseteq Ab^2$ .

By considering these ideas in the context of the augmented database, we can also define how to reason abductively on the event rules. In this case, abducible predicates correspond to base event facts since this is the only possible way to physically update a database.

##### Definition 4

Let us consider a deductive database  $D = (EDB, IDB)$  and its corresponding augmented database  $A(D) = (EDB, IDB^*)$ . We can define an associated abductive framework  $\prec EDB \cup IDB^*, Ab \succ$ , where  $Ab$  corresponds to the set of base event predicates. Now, given a ground derived event  $u$ , we can define an *abductive explanation for  $u$*  in  $\prec EDB \cup IDB^*, Ab \succ$  to be any set  $T_i$  consisting of ground facts about predicates in  $Ab$  such that:

$$- EDB \cup IDB^* \cup T_i \models u$$

An explanation  $T_i$  is *minimal* if no proper subset of  $T_i$  is also an explanation, i.e. if it does not exist any explanation  $T_j$  for  $u$  such that  $T_j \subset T_i$ .

The previous condition states that the update request is a logical consequence of the database updated according to  $T_i$ . Thus, abductive reasoning on the event rules defines changes on base predicates needed to satisfy a given change on a derived predicate.

As an example, given the database of Example 2 and the derived event  $\iota\text{Cont}(\text{John})$ , it is not difficult to see that  $T = \{\delta\text{Fail-ex}(\text{John})\}$  is a minimal abductive explanation

<sup>2</sup> Here and in the rest of the paper we will use  $Ab$  to indicate both the set of abducible predicates and the set of all their variable-free instances.

for  $\iota\text{Cont}(\text{John})$ . That is, the insertion of  $\text{Cont}(\text{John})$  is satisfied by the deletion of  $\text{Fail-ex}(\text{John})$ .

In general, the result of applying abductive reasoning may not be unique. That is, several sets  $T_i$  of base event facts that satisfy a derived event may exist. Each possible set  $T_i$  constitutes a possible transaction that applied to the database will accomplish the desired change on the derived predicate. Minimal explanations are usually of particular interest, specially when we deal with database updating problems since they allow to minimize the difference between the old and the new states of the database.

If no solution  $T_i$  is obtained then either the requested update cannot be satisfied only by changes on the EDB or the current database state already satisfies the intended effect of the request (e.g. an insertion of  $P$  is requested into a database that already satisfies  $P$ ). Note that in the latter case we do not obtain a solution with the empty set since, when taking the event definition into account, an insertion of  $P$  can only be explained if the old state of the database does not satisfy  $P$  (resp. a deletion of  $P$  can only be explained if  $P$  is satisfied).

With this framework, the basic strategy of a proof procedure for computing  $T_i$  is the following. Given, for instance, an update request for inserting  $P$ , the update procedure tries to solve abductively the goal  $\leftarrow \iota P$  in  $\prec \text{EDB} \cup \text{IDB}^*, Ab \succ$  generating a set  $T_i$  of abducibles such that  $T_i$  satisfies the above condition. Before abducting a base event, we have to check that its definition is satisfied. That is, for abducting an event  $\delta P$  we require  $P$  to be true in the old state of the database while for  $\iota P$  we require  $P$  to be false. The set  $T_i$  generated by abduction for an update request  $u$  constitutes a transaction that, applied to the current state of the EDB, will satisfy  $u$ .

Given an event (base or derived)  $u_i$  to be explained, abductive reasoning on the event rules can also be used to determine sets of base events that ensure that a certain derived event  $u_j$  is not induced by the explanations of  $u_i$ . In this case, the abductive interpretation defines changes on base predicates needed to satisfy that a certain change on a derived predicate does not occur as a consequence of the application of the explanations of  $u_i$ .

*Definition 5*

Let  $D$  be a deductive database  $D = (\text{EDB}, \text{IDB})$ , its corresponding augmented database  $A(D) = (\text{EDB}, \text{IDB}^*)$  and its associated abductive framework  $\prec \text{EDB} \cup \text{IDB}^*, Ab \succ$ . Now, given a positive event  $u_i$  and a negative derived event  $\neg u_j$  such that  $u_i \wedge \neg u_j$  is allowed, we can define the abductive explanation for  $u_i \wedge \neg u_j$  in  $\prec \text{EDB} \cup \text{IDB}^*, Ab \succ$  to be any set  $T_i$  consisting of ground facts about predicates in  $Ab$  such that:

- $\text{EDB} \cup \text{IDB}^* \cup T_i \models u_i$
- $\text{EDB} \cup \text{IDB}^* \cup T_i \not\models u_j$

The first condition states that  $u_i$  is a logical consequence of the database updated according to  $T_i$ , while the second states that  $u_j$  it is not. Note that if the explanations of  $u_i$  alone do not induce  $u_j$ , then they are already valid abductive explanations.

As an example, given the database of Example 2 and the positive event  $\iota\text{Sign}(\text{Mary})$  and the negative event  $\neg\iota\text{Cont}(\text{Mary})$ , we have that  $T = \{\iota\text{Sign}(\text{Mary}), \iota\text{Fail-ex}(\text{Mary})\}$  is a minimal abductive explanation for  $\iota\text{Sign}(\text{Mary}) \wedge \neg\iota\text{Cont}(\text{Mary})$ . Note that  $\iota\text{Sign}(\text{Mary})$  alone would induce  $\iota\text{Cont}(\text{Mary})$ . However, adding  $\iota\text{Fail-ex}(\text{Mary})$  to  $T$  does not induce  $\iota\text{Cont}(\text{Mary})$  any more since  $\text{Cont}(\text{Mary})$  will be false in the new database state.

Two special cases are of particular interest. First, when the negative derived event is  $\neg\iota\text{Ic}$  it is guaranteed that the obtained explanations do not induce any insertion of an integrity constraint. Thus, the new database state will be consistent if the old database state was already consistent. Second, if the positive event is base (i.e. a transaction  $T$ ), abductive reasoning on the event rules determines possible sets  $S_i$  of ground base event facts that, appended to  $T$ , ensure that the application of any of the resulting transactions  $T_i = S_i \cup T$  does not induce  $u_j$ . Note that if  $T$  alone does not induce  $u_j$ , then  $T$  itself is a valid transaction.

This framework can be easily generalized to reason abductively on sets of positive and negative events.

## 5 Deductive or Abductive Nature of Database Problems

Deduction and abduction provide a uniform way to reason about the event rules and, in general, about any set of rules that explicitly define the exact difference between two consecutive database states. Moreover, either views (i.e. derived predicates) or integrity constraints or conditions to be monitored are uniformly defined by means of deductive rules and they are only distinguished by the different semantics endowed to the head of the rule. Thus, a view defines common knowledge shared by different users, an integrity constraint defines a situation that must never happen and a condition to be monitored defines an information whose changes must be reported to the user.

Therefore, given a derived predicate  $P(x)$  defined by the rule  $P(x) \leftarrow Q(x) \wedge \neg R(x)$ ,  $P$  can be expressed as:

$$\begin{aligned} \text{View}(x) &\leftarrow Q(x) \wedge \neg R(x) \\ \text{Ic1}(x) &\leftarrow Q(x) \wedge \neg R(x) \\ \text{Cond}(x) &\leftarrow Q(x) \wedge \neg R(x) \end{aligned}$$

according to the concrete semantics that we would like to endow to  $P$ .

Now, reasoning deductively or abductively on the event rules corresponding to  $\text{View}$ ,  $\text{Ic1}$  and  $\text{Cond}$  we may classify as naturally deductive or naturally abductive the database schema validation and update processing problems.

This is summarized in Table 1. Each row corresponds to the form of reasoning to be applied to the event rules of  $P$  and to the relevant events about  $P$  (i.e.  $\iota P$ ,  $\delta P$ ,  $T \wedge \neg\iota P$  or  $T \wedge \neg\delta P$ ; being  $T$  a transaction) to reason about. Each column considers a different semantics to be endowed to  $P$ . Finally, each resulting cell defines a possible database schema validation or update processing problem that can be specified in terms of that form of reasoning and of the considered semantics.

In the rest of this section, we briefly review database schema validation and

		View	Ic	Cond
<b>Deduced Consequences on</b> (deductive reasoning)	$\neg P$	Materialized view maintenance	IC checking	Condition Monitoring
	$\delta P$		Checking consistency restoration	
<b>Abductive Explanation for</b> (abductive reasoning)	$\neg P$	View updating	Redundancy of Integrity Constraints	Enforcing condition activation
	$\delta P$	View liveness	Repairing inconsistent DB Satisfiability Checking	Condition validation
	$T \wedge \neg P$	Preventing side effects	IC maintenance	Preventing condition activation
	$T \wedge \neg \delta P$		Maintaining DB inconsistency	

Table 1. Classification of Database Problems

update processing problems and we show how they can be handled by means of deductive or abductive reasoning, according to the classification provided in Table 1.

### 5.1 Schema Validation and Update Processing Problems

The correct use of a database involves three different tasks: *Schema Validation*, to guarantee that the database schema satisfies the user's intended needs and requirements; *Query Processing*, to be able to give efficient and correct answers to the user's queries; and *Update Processing*, to be able to correctly perform updates to the database contents. In general, several problems may arise when dealing with each of these tasks (Teniente 2000). We will consider here only the problems encountered during schema validation and update processing, since query processing is beyond the scope of this paper.

#### Example 3

Consider the following flawed database schema to be validated:

- (DR.1)  $\text{Some-cand} \leftarrow \text{Cand}(x)$
- (DR.2)  $\text{Emp}(x) \leftarrow \text{Cand}(x) \wedge \text{Cont}(x)$
- (DR.3)  $\text{Cont}(x) \leftarrow \text{Sign}(x) \wedge \neg \text{Fail-ex}(x)$
- (DR.4)  $\text{App}(x) \leftarrow \text{Cand}(x)$
- (IC.1)  $\text{Ic1}(x) \leftarrow \text{App}(x) \wedge \text{Sign}(x)$
- (IC.2)  $\text{Ic2}(x) \leftarrow \text{App}(x) \wedge \neg \text{Has-account}(x)$
- (IC.3)  $\text{Ic3}(x) \leftarrow \neg \text{Some-cand}$
- (IC.4)  $\text{Ic4}(x) \leftarrow \text{Cand}(x) \wedge \neg \text{App}(x)$
- (IC.5)  $\text{Ic5}(x) \leftarrow \text{App}(x)$
- (IC.6, ..., IC.10)  $\text{Ic} \leftarrow \text{Ici}$ , for  $i=1\dots5$
- (Cond.1)  $\text{Cond1}(x) \leftarrow \text{Cand}(x) \wedge \neg \text{Cont}(x)$

$$(\text{Cond.2}) \quad \text{Cond2}(x) \leftarrow \text{Emp}(x) \wedge \neg \text{Cont}(x)$$

This schema defines four derived predicates (through deductive rules DR.1 to DR.4): Some-cand, Emp (employee), Cont (contracted person) and App (applicant). A person is an applicant if he is a candidate (Cand). A person is contracted if he signed an agreement (Sign) and he did not fail the exam. Employees are candidates that have a contract. Finally, Some-cand is true if the database contains, at least, one candidate.

The schema contains also five integrity constraints (defined by integrity rules IC.1 to IC.5). Ic1 states that it is not possible to have applicants that have signed an agreement. Ic2 states that it is not possible to be applicant and not to have an account. Ic3 states that there must be some candidate. Ic4 states that it is not possible to be candidate and not be applicant. Finally, Ic5 states that the database may not contain any applicant.

The schema contains also two conditions to be monitored. The first one is used to notify changes on the populations of applicants that do not have a contract and the second one changes on the populations of employees that do not have a contract.

## 5.2 Schema Validation Problems

In general, we cannot be completely sure that a certain database schema adequately describes the structure of the information that we want the database to contain. At first glance, we could perhaps detect that a certain deductive rule or integrity constraint is not precisely defined, as it might happen with IC.5 above, but it is very difficult to assess whether a certain schema does not present critical flaws. Detecting and removing flaws during schema design time will prevent these flaws from materializing as run-time errors or other inconveniences during operation time. (Decker et al. 1996) identified several desirable properties that a database schema should satisfy.

### 5.2.1 Satisfiability Checking

A database schema is *satisfiable* if there exists an EDB for which no integrity constraint is violated (Bry and Manthey 1986), also mentioned in (Bry, Decker and Manthey 1988, Inoue, Koshimura and Hasegawa 1992). Clearly, a non-satisfiable schema is not useful since it does not accept any extensional information.

As an example, the previous database schema is not satisfiable for any EDB. The empty EDB is not a proper EDB since it violates Ic3. Then, we need to consider an EDB with at least one candidate, let us say John. However, this is not enough since Ic4 would then be violated. So, John must also be an applicant but this is not possible since Ic5 impedes it. As a consequence of detecting that the previous schema is not satisfiable, we assume that the database designer decides to discard Ic3 and Ic5.

*Satisfiability checking* can be naturally specified as performing abductive reasoning on the event rules associated to  $\delta\text{Ic}$  provided that Ic holds with an empty EDB.

If there exists at least one abductive explanation for  $\delta Ic$  in  $\prec EDB \cup IDB^*$ ,  $Ab \succ$ , with  $IDB = DR \cup IC$ , then the integrity constraints are satisfiable. Note that if  $Ic$  does not hold in the state corresponding to the empty EDB, all constraints are already satisfied in that state.

Note that, since satisfiability checking is to be determined at schema validation time, we are considering the empty EDB for checking this property. For the same reason, we will also use the empty EDB for checking other problems related to database schema validation.

### 5.2.2 Absolute Redundancy of an Integrity Constraint

Intuitively, an integrity constraint is absolutely redundant if integrity does not depend on it. That is, if it can never be violated. Obviously, an absolute redundant integrity constraint is not useful since it does not add any additional information to the information already provided by the rest of the schema.

For instance, integrity constraint  $Ic_4$  is absolutely redundant since the deductive rule DR.4 prevents  $Ic_4$  to be violated for any EDB. Therefore, the database designer has to modify the schema to remove this absolute redundancy. In this case, we assume that he decides to discard DR.4.

Given an integrity constraint  $Ic_i$ , *absolute redundancy* can be naturally specified as performing abductive reasoning on the event rules associated to  $\iota Ic_i$ . If there exists at least one abductive explanation for  $\iota Ic_i$  in  $\prec EDB \cup IDB^*$ ,  $Ab \succ$ , with  $IDB = DR \cup IC$ , then  $Ic_i$  is not absolutely redundant since it can be violated in some state of the database. In particular, in the database state that we obtain as a result of applying the obtained abductive explanation.

### 5.2.3 View Liveliness

A derived predicate  $P$  (i.e. a view) is *lively* if there exists an EDB in which at least one fact about  $P$  is true. That is, predicates which are not lively correspond to views that are empty in each possible state of the database. Such predicates are clearly not useful and probably ill-specified. This definition of “liveliness” essentially coincides with the definition of “satisfiable” in (Levy and Sagiv 1995).

For instance, predicate  $Emp$  as defined in Example 3 is not lively. The reason is that a fact  $Emp(X)$  requires  $Cand(X)$  and  $Sign(X)$  to be true at the same time. However, since nobody can be a candidate without being an applicant ( $Ic_4$ ) and nobody can be an applicant and to have signed an agreement ( $Ic_1$ ), no person  $X$  can be an employee. We assume that the database designer decides to correct this flaw by redefining  $Ic_1$  as  $Ic_1'(x) \leftarrow App(x) \wedge Sign(x) \wedge \neg Has-account(x)$ .

In our framework, provided that no fact about View holds in the empty EDB, *view liveliness* can be specified as reasoning abductively on the event rules of  $\iota View(\mathbf{x})$ . If there exists at least one abductive explanation for a certain event  $\iota View(\mathbf{X})$  in  $\prec EDB \cup IDB^*$ ,  $Ab \succ$ , then View is lively since it is possible to reach a state where at least a fact  $View(\mathbf{X})$  is true. Otherwise, View is not lively. Note that if some fact



about View holds in the empty EDB, then View is already lively in that state and there is no reason to ask about this property.

Let us review the Example 3 with the flaws corrected up to now:

(DR.1)	Some-cand $\leftarrow$ Cand(x)
(DR.2)	Emp(x) $\leftarrow$ Cand(x) $\wedge$ Cont(x)
(DR.3)	Cont(x) $\leftarrow$ Sign(x) $\wedge$ $\neg$ Fail-ex(x)
(IC.1')	Ic1(x) $\leftarrow$ App(x) $\wedge$ Sign(x) $\wedge$ $\neg$ Has-account(x)
(IC.2)	Ic2(x) $\leftarrow$ App(x) $\wedge$ $\neg$ Has-account(x)
(IC.4)	Ic4(x) $\leftarrow$ Cand(x) $\wedge$ $\neg$ App (x)
(IC.6, IC.7, IC.9)	Ic $\leftarrow$ Ici, for i=1,2, 4.
(Cond.1)	Cond1(x) $\leftarrow$ Cand(x) $\wedge$ $\neg$ Cont (x)
(Cond.2)	Cond2(x) $\leftarrow$ Emp(x) $\wedge$ $\neg$ Cont (x)

#### 5.2.4 Relative Redundancy of Integrity Constraints

Relative redundancy is similar to absolute redundancy but, in this case, an integrity constraint (or a set of constraints) is relatively redundant if it is always satisfied in all states that satisfy the rest of the constraints. Again, such a redundancy should be detected and redundant constraints should not be considered during update processing.

In our example, we can see that Ic1' is relatively redundant since it is entailed by Ic2. Therefore, we assume that the database designer decides to discard Ic.1' since the resulting database will admit the same consistent states.

Given an integrity constraint  $Ic_i$ , *relative redundancy* can be naturally specified as performing abductive reasoning on the event rules associated to  $\iota Ic_i$ .  $Ic_i$  is not relatively redundant if there exists at least one abductive explanation for  $\leftarrow \iota Ic_i \wedge \neg \iota Ic$  in  $\prec$  EDB  $\cup$  IDB\*,  $Ab \succ$ , with IDB = DR  $\cup$  IC -  $\{ Ic \leftarrow Ic_i \}$ .

#### 5.2.5 Condition Validation

Condition validation refers to the problem of determining whether it is possible to change the contents of a certain condition Cond(x). That is, to determine whether exists at least one transaction that, if applied to the database, could activate a certain condition  $\iota$ Cond(**X**) or  $\delta$ Cond(**X**). Clearly, a condition that can never be activated is probably ill-specified since the active behaviour of the database does not depend on it. This can be useful, for instance, to provide the database designer with a tool for validating certain aspects of the condition definition and, hence, of the active behaviour of the database. This problem is very important in the context of active databases since this technology is mainly based on the extensive use of conditions to be monitored, which are the core of Condition-Action (CA) and Event-Condition-Action (ECA) rules (Widom and Ceri 1996).

For instance, condition Cond2 as defined in Example 3 is not valid since no insertion and no deletion can be induced on it. The reason is that, by the deductive rule DR.2, employees must have a contract and, then, it is not possible to have

employees without a contract. So, we assume that the database designer decides to discard condition Cond2.

In a similar way that view liveness, changes induced in a given condition,  $\text{Cond}(\mathbf{x})$ , can be specified as reasoning abductively on the event rules of  $\iota\text{Cond}(\mathbf{x})$  and  $\delta\text{Cond}(\mathbf{x})$ . If there exists at least one abductive explanation for a certain event  $\iota\text{Cond}(\mathbf{X})$  or  $\delta\text{Cond}(\mathbf{X})$  in  $\prec \text{EDB} \cup \text{IDB}^*, \text{Ab} \succ$ , then the condition can be activated.

### 5.3 Update Processing Problems

Once the database schema is validated, we are ready to perform updates to the database contents. Several problems will arise when processing the requested updates (Teniente and Urpí 1995). To illustrate these problems, we consider the schema we have previously validated and we will assume that the database contains several base facts. Note that, now, the schema is satisfiable, all predicates are lively and no integrity constraint is either absolutely nor relatively redundant.

#### Example 4

The following database will be considered to deal with update problems related to views and integrity constraints:

(F.1)	$\text{Sign}(\text{John})$
(F.2)	$\text{Fail-ex}(\text{John})$
(DR.1)	$\text{Some-cand} \leftarrow \text{Cand}(\mathbf{x})$
(DR.2)	$\text{Emp}(\mathbf{x}) \leftarrow \text{Cand}(\mathbf{x}) \wedge \text{Cont}(\mathbf{x})$
(DR.3)	$\text{Cont}(\mathbf{x}) \leftarrow \text{Sign}(\mathbf{x}) \wedge \neg \text{Fail-ex}(\mathbf{x})$
(IC.2)	$\text{Ic2}(\mathbf{x}) \leftarrow \text{App}(\mathbf{x}) \wedge \neg \text{Has-account}(\mathbf{x})$
(IC.4)	$\text{Ic4}(\mathbf{x}) \leftarrow \text{Cand}(\mathbf{x}) \wedge \neg \text{App}(\mathbf{x})$
(IC.7, IC.9)	$\text{Ic} \leftarrow \text{Ici}, \text{ for } i=2, 4.$
(Cond.1)	$\text{Cond1}(\mathbf{x}) \leftarrow \text{Cand}(\mathbf{x}) \wedge \neg \text{Cont}(\mathbf{x})$

#### 5.3.1 Integrity Constraint Checking

There exists a large cumulative effort in the field of *integrity constraint checking* (Sadri and Kowalski 1988, Küchenhoff 1991, Olivé 1991, García et al. 1994, Lee and Ling 1996, Staudt and Jarke 1996). Given a consistent database and a transaction (i.e. a set of insertions and deletions of base facts), integrity constraint checking is devoted to incrementally, i.e. efficiently, determine whether the application of this transaction to the current database violates some integrity constraint. In this case, the transaction is rejected since, otherwise, its application would lead to an inconsistent database state.

Given a transaction  $T$ , *integrity constraint checking* can be naturally specified in our framework as performing deductive reasoning on the event rules associated to  $\iota\text{Ic}$ , provided that  $\text{Ic}$  does not hold. The deduced consequences on  $\iota\text{Ic}$  are either the identity substitution or no correct answer of  $\text{EDB} \cup \text{IDB}^* \cup T \cup \neg \iota\text{Ic}$  exists. In the first case,  $T$  induces an insertion of  $\text{Ic}$  and, therefore, it must be rejected

because it violates some integrity constraint. Otherwise,  $T$  does not violate any integrity constraint and it can be successfully applied. As it happens with materialized view maintenance, efficiency of the process is ensured since reasoning about the transaction and the event rules allows to compute only the updates induced by this transaction.

As an example, assume that the database of Example 4 contains also the facts  $\text{App}(\text{Peter})$  and  $\text{Has-account}(\text{Peter})$ . Reasoning deductively on the event rules of  $\text{Ic2}$  we could determine that the transaction  $T = \{\delta\text{Has-account}(\text{Peter})\}$  induces the insertion of  $\text{Ic2}(\text{Peter})$  and, thus, of  $\text{Ic}$  and would lead the database to an inconsistent state.

### 5.3.2 Integrity Constraint Maintenance

The main drawback of integrity constraint checking is that the user may not know which changes to the transaction are needed to guarantee that its application does not violate any integrity constraint. *Integrity constraint maintenance* is aimed at overcoming this drawback: given a consistent database state and a transaction  $T$  that violates some integrity constraint, the problem is to find *repairs*, that is, an additional set of insertions and/or deletions of base facts to be appended to  $T$  such that the resulting transaction  $T'$  satisfies all integrity constraints. In general, there may be several repairs and the user must select one of them. Eventually, if no such repair exists then the original transaction must be rejected. Several methods have been proposed to deal with this problem (Moerkotte and Lockemann 1991, Ceri et al. 1994, Wüthrich 1993, Schewe and Thalheim 1994, Teniente and Olivé 1995).

Given a consistent database state and a transaction  $T$ , *integrity constraint maintenance* can be specified in our framework as performing abductive reasoning on the goal  $\leftarrow T \wedge \neg \text{Ic}$ . Thus, possible abductive explanations for  $T \wedge \neg \text{Ic}$  in  $\prec \text{EDB} \cup \text{IDB}^*$ ,  $Ab \succ$ , with  $\text{IDB} = \text{DR} \cup \text{IC}$ , correspond to the possible transactions  $T'$ ,  $T \subseteq T'$ , that maintain database consistency.

As an example, consider again the database of Example 4 and assume that the transaction  $T = \{\iota\text{App}(\text{Claire})\}$  wants to be applied to the database. Reasoning abductively on  $\iota\text{App}(\text{Claire}) \wedge \neg \text{Ic}$  we obtain the transaction  $T' = \{\iota\text{App}(\text{Claire}), \iota\text{Has-account}(\text{Claire})\}$  which satisfies the original transaction and maintains the database consistent.

### 5.3.3 View Updating

*View updating* is concerned with determining how a request to update a view, i.e. to update the contents of a derived predicate, must be appropriately translated into updates of the underlying base facts. In general, several translations may exist and the user must select one of them. This problem has attracted much research during the last years in deductive databases (Kakas and Mancarella 1990, Guessoum and Lloyd 1990, Teniente and Olivé 1995, Console et al. 1995, Decker 1996, Lobo and Trajcevski 1997) and it has been already identified as an abductive problem

(Console et al. 1995, Decker 1996, Denecker and Schreye 1998, Inoue and Sakama 1999)

*View updating* can be naturally specified as performing abductive reasoning on the event rules of  $\iota\text{View}(\mathbf{X})$  or  $\delta\text{View}(\mathbf{X})$ , where  $\text{View}(\mathbf{X})$  is the derived fact to be inserted or deleted, respectively. The abductive explanation for  $\iota\text{View}(\mathbf{X})$  defines possible sets of base fact updates (i.e. transactions) that satisfy the insertion of  $\text{View}(\mathbf{X})$ , while the abductive explanation for  $\delta\text{View}(\mathbf{X})$  defines possible sets of base fact updates that satisfy the deletion of  $\text{View}(\mathbf{X})$ .

For instance, in Example 4 reasoning abductively on the event rules of Cont we can determine that the view update request  $\iota\text{Cont}(\text{John})$  is satisfied by the transaction  $T=\{\delta\text{Fail-ex}(\text{John})\}$ .

In principle, it may happen that some translations corresponding to a given view update request do not satisfy the integrity constraints. For this reason, view updating is usually combined with problems related to integrity constraints. Possible ways of performing this combination will be explained in Section 5.5.

#### 5.3.4 Materialized View Maintenance

A view can be materialized by explicitly storing its contents in the extensional database. This can be useful, for instance, to improve efficiency of query processing. Given a transaction, *materialized view maintenance* consists of incrementally, i.e. efficiently, determining which changes are needed to update accordingly the materialized views (see (Gupta and Mumick 1995, Roussopoulos 1998) for a state-of-the-art reports).

Given a transaction  $T$  and a materialized view  $\text{View}(\mathbf{x})$ , *materialized view maintenance* can be naturally specified as performing deductive reasoning on the event rules associated to  $\iota\text{View}(\mathbf{x})$  and  $\delta\text{View}(\mathbf{x})$ . That is, deduced consequences for  $\iota\text{View}(\mathbf{x})$  and for  $\delta\text{View}(\mathbf{x})$  correspond, respectively, to the insertions and to the deletions to be performed on  $\text{View}(\mathbf{x})$ . Efficiency of the process is ensured since reasoning about the transaction and the event rules allows to incrementally compute only the updates induced by this transaction.

For instance, if we assume that predicate  $\text{Cont}(\mathbf{x})$  in Example 4 is materialized, reasoning deductively on the event rules of Cont we can determine that the transaction  $T=\{\delta\text{Fail-ex}(\text{John})\}$  induces the insertion of  $\text{Cont}(\text{John})$  in the materialized view.

#### 5.3.5 Preventing Side Effects

Due to the deductive rules, undesired updates may be induced on some derived predicates when applying a transaction. We say that a side effect occurs when this happens. The problem of *preventing side effects* (Teniente and Olivé 1995) is concerned with determining a set of base fact updates which, appended to a given transaction, ensure that the application of the resulting transaction to the current state of the database will not induce the undesired side effects. In general, several solutions may exist and the user must select one of them.

Ensuring that a transaction  $T$  will not induce an insertion or a deletion of a derived fact  $\text{View}(\mathbf{X})$  can naturally be specified as reasoning abductively on  $\{T \wedge \neg \iota \text{View}(\mathbf{X})\}$  or on  $\{T \wedge \neg \delta \text{View}(\mathbf{X})\}$ , respectively. The former defines sets  $T'$  of base fact updates, which are supersets of  $T$ , needed to guarantee that the insertion of  $\text{View}(\mathbf{X})$  is not induced by  $T$ , while the latter defines sets  $T'$  of base fact updates, again supersets of  $T$ , needed to satisfy that the deletion of  $\text{View}(\mathbf{X})$  is not induced.

For instance, reasoning abductively on  $\iota \text{Sign}(\text{Mary}) \wedge \neg \iota \text{Cont}(\text{Mary})$  we can prevent that the transaction  $T = \{\iota \text{Sign}(\text{Mary})\}$  will not induce the insertion of  $\text{Cont}(\text{Mary})$ . This is done by considering  $T' = \{\iota \text{Sign}(\text{Mary}), \iota \text{Fail-ex}(\text{Mary})\}$  instead of  $T$ , which is also given by this abductive interpretation.

### 5.3.6 Condition Monitoring

*Condition monitoring* refers to the problem of incrementally monitoring the changes on a condition induced by a transaction that consists of a set of base fact updates (Rosenthal et al. 1989, Hanson et al. 1990, Qian and Widerhold 1991, Baralis et al. 1998).

As an example, applying the transaction  $T = \{\iota \text{Cand}(\text{Peter})\}$  to the database of Example 4 would induce  $\iota \text{Cond1}(\text{Peter})$ . That is, due to the application of  $T$ , Peter would be a candidate without a contract.

In our framework, changes induced in a condition  $\text{Cond}(\mathbf{x})$ , are specified as performing deductive reasoning on the events rules associated to  $\iota \text{Cond}(\mathbf{x})$  and  $\delta \text{Cond}(\mathbf{x})$ . The former,  $\iota \text{Cond}(\mathbf{x})$ , defines the changes meaning that  $\mathbf{x}$  satisfy the condition after the application of the transaction, but not before. The latter,  $\delta \text{Cond}(\mathbf{x})$ , defines the changes meaning that  $\mathbf{x}$  satisfy the condition before the application of the transaction, but not after.

### 5.3.7 Enforcing Condition Activation

*Enforcing condition activation* refers to the problem of obtaining the possible transactions that, if applied to the current state of the database, would induce an activation of a given condition. For instance, the transaction  $T_1 = \{\iota \text{Cand}(\text{Peter})\}$  would induce the condition  $\iota \text{Cond1}(\text{Peter})$ .

In our framework, enforcing condition activation is specified reasoning abductively on  $\iota \text{Cond}(\mathbf{X})$  or  $\delta \text{Cond}(\mathbf{X})$ , where both correspond to the conditions to be enforced. The former defines possible transactions that will induce  $\mathbf{X}$  to satisfy the condition after their application, but not before. The latter, defines possible transactions that will induce  $\mathbf{X}$  not to satisfy the condition after their application.

### 5.3.8 Preventing Condition Activation

This problem is close to the problem of preventing side effects but considering conditions to be monitored instead of views. Given a transaction  $T$ , the problem of *preventing condition activation* is to find an additional set of insertions and/or deletions of base facts to be appended to  $T$  such that the resulting transaction  $T'$

guarantees that no changes in the condition would occur as a consequence of the application of  $T'$ . In general, several resulting transactions may exist and the user should select one of them.

#### 5.4 Updates to an Inconsistent Database

Sometimes it could be useful to allow for intermediate inconsistent database states, i.e. states where some integrity constraint is violated. This may happen, for instance, to reduce the number of times that integrity constraint enforcement is performed. In this case, three new problems related to update processing arise.

##### 5.4.1 Checking Consistency Restoration

Given an inconsistent database state and a transaction that consists of a set of base fact updates, the problem of *checking consistency restoration* is to incrementally check whether these updates restore the database to a consistent state.

*Checking consistency restoration* can be specified as performing deductive reasoning on  $\delta Ic$ , provided that  $Ic$  holds. In this case, deduced consequences on  $\delta Ic$  are also either the identity substitution or no correct answer exists. If the identity substitution is obtained, then the transaction induces a deletion of  $Ic$  and, therefore, restores the database to a consistent state.

##### 5.4.2 Repairing an Inconsistent Database

Given an inconsistent database state, the problem of *repairing an inconsistent database* is to obtain a set of updates of base facts, i.e. a transaction, that restore the database to a consistent state. In general, several solutions may exist and the database administrator should select one of them.

The problem of *repairing an inconsistent database* can be specified as performing abductive reasoning on the event rules associated to  $\delta Ic$ , provided that  $Ic$  holds. Given an EDB that violates some integrity constraint, abductive explanations for  $\delta Ic$  in  $\prec EDB \cup IDB^*$ ,  $Ab \succ$ , with  $IDB = DR \cup IC$ , correspond to the possible transactions that would induce a deletion of  $Ic$  and that, therefore, would restore database consistency.

##### 5.4.3 Maintaining Database Inconsistency

Given an inconsistent database state and a transaction  $T$ , the problem of *maintaining database inconsistency* is to obtain an additional set of base fact updates to be appended to the original transaction to guarantee that the resulting database state remains inconsistent.

*Maintaining database inconsistency* can be specified as performing abductive reasoning on the goal  $\leftarrow T \wedge \neg \delta Ic$ , provided that  $Ic$  holds, with an abductive framework  $\prec EDB \cup IDB^*$ ,  $Ab \succ$ , with  $IDB = DR \cup IC$ . Although we do not see for the moment any practical application of this problem, it can be naturally classified and specified in the framework we propose in this paper.

### 5.5 Combining Different Problems

In previous sections, we have assumed that deductive or abductive reasoning is performed on the event rules associated to a single derived event predicate. However, this framework can be easily extended to consider several derived events instead of only one. Deductive or abductive reasoning on a set of derived events is performed by considering the conjunction of all derived events in the set as the goal to be reasoned about. For instance a view update request consists, in general, of a set of insertions and/or deletions to be performed on derived predicates, e.g.  $u = \iota P(a) \wedge \iota Q(b) \wedge \delta S(c)$  stands for the request of inserting  $P(a)$  and  $Q(b)$  and deleting  $S(c)$ , being  $P$ ,  $Q$  and  $S$  derived predicates. In this case, translations that satisfy  $u$  correspond to the abductive explanations for  $\iota P(a) \wedge \iota Q(b) \wedge \delta S(c)$  in  $\prec EDB \cup IDB^*, Ab \succ$ .

Moreover, we would like to notice that deductive problems can be naturally combined. All of them share a common starting-point (a transaction that consists of a set of base fact updates) and aim at the same goal (to define the changes on derived predicates induced by this transaction). The same reasons allow the combination of abductive problems. Therefore, we can specify more complex database updating problems of deductive or of abductive by considering possible combinations of the problems specified in section 5.

For instance, given a transaction  $T$ , a materialized view  $View$ , a condition to be monitored  $Cond$  and the integrity constraint predicate  $Ic$ , we could combine materialized view maintenance, integrity constraints checking and condition monitoring by reasoning deductively on  $\iota View(\mathbf{x}) \wedge \delta Cond(\mathbf{y}) \wedge \neg \iota Ic$ . Deduced consequences on  $\iota View(\mathbf{x}) \wedge \delta Cond(\mathbf{x}) \wedge \neg \iota Ic$  correspond to the values  $\mathbf{x}$  and  $\mathbf{y}$  that cause an insertion of  $View$ , satisfy the condition  $\delta Cond$  as a consequence of the application of  $T$ , and such that  $T$  does not violate any integrity constraint.

In a similar way, we could also combine view updating with integrity constraints maintenance by reasoning abductively on  $\iota View(a) \wedge \neg \iota Ic$ . In this case, abductive explanations for  $\iota View(a) \wedge \neg \iota Ic$  correspond to the translations that satisfy both the insertion of  $View(a)$  and that do not violate any integrity constraint.

Furthermore, we could also combine deductive and abductive problems. Note that the result of performing abductive reasoning is exactly the starting-point for performing deductive reasoning, that is, a transaction that consists of a set of base fact updates. Therefore, we could first deal with abductive problems and, immediately after, use the obtained result for dealing with the deductive ones.

For instance, we could be interested on distinguishing between integrity constraints to be maintained and integrity constraints to be checked, and on combining view updating with the treatment of both kinds of constraints. In this case, we should first reason abductively on the view update request and the set of integrity constraints to be maintained and, later on, to consider the resulting transactions and reason deductively on the set of integrity constraints to be checked to reject those resulting transactions that violate some constraint in this set.

Finally, we would also like to notice that in our approach for the specification of database updating problems does not change when considering other kinds of

updates like insertions or deletions of deductive rules. In this case, we should first determine the changes on the transition and event rules caused by the update and apply then our approach.

## 6 Using Existing Procedures to Reason on the Event Rules

Our framework to classify database schema validation and updating processing problems is based on the existence of a set of rules, like the event rules, that define the exact difference between consecutive database states. By performing deductive and abductive reasoning on these rules, we can deal with all these problems in a uniform way. Therefore, our framework does not rely on the concrete method we use to perform either deductive or abductive reasoning. However, candidate methods to be used must satisfy several conditions.

Given a method able to perform deductive reasoning in a certain class of deductive databases, it should satisfy two requirements to tackle the deductive problems described in the previous section:

- a) The class of deductive databases considered by the method must allow expressing at least the goals required to define these problems.
- b) The method must obtain all correct answers that satisfy the request.

Similarly, given a method able to perform abductive reasoning in a certain class of deductive databases, it should satisfy two requirements to tackle the abductive problems described in the previous section:

- a) The class of deductive databases considered by the method must allow expressing at least the goals required to define these problems.
- b) For schema validation problems, if there exists some explanation for a given request the method obtains such explanation (but not necessarily several or even all of them). For updating problems, the method must be complete, i.e. it must obtain all possible explanations that satisfy the request.

In this section we show that there exists already some procedures able to compute each different form of reasoning on the event rules and we illustrate them by means of some examples. We show, in this way, the applicability of our approach. We would like to mention, however, that our aim is not that of comparing existing procedures but just to show they are able to handle several problems.

### 6.1 Using SLDNF to Reason Deductively on the Event Rules

Standard SLDNF resolution is a possible way for reasoning deductively on the event rules. Given an augmented database  $A(D) = (EDB, IDB^*)$ , a transaction  $T$  and a derived event  $u$ , the deduced consequences on  $u$  due to  $T$  correspond to the successful SLDNF derivations of the goal  $\leftarrow u$  that result in a computed answer  $\theta_i$  when considering the input set  $EDB \cup IDB^* \cup T$ .

Nevertheless, other proof procedures could be used instead of SLDNF resolution



like, for instance, bottom-up computation of the event rules. To motivate our discussion and without loss of generality, we will assume that SLDNF resolution is used to reason deductively on the event rules. The following example illustrates how to perform deductive reasoning on the event rules.

*Example 5*

Consider again Example 2 and assume a transaction  $T$  which consists of the deletion of the base fact  $\text{Fail-ex}(\text{John})$ , in our notation  $T = \{\delta\text{Fail-ex}(\text{John})\}$ . The corresponding deductive framework is:

EDB  $\cup$  IDB\*:     $\text{Sign}(\text{John})$   
                        $\text{Fail-ex}(\text{John})$   
                        $\text{Cont}(x) \leftarrow \text{Sign}(x) \wedge \neg\text{Fail-ex}(x)$   
                        $\iota\text{Cont}(x) \leftarrow \text{Sign}(x) \wedge \neg\delta\text{Sign}(x) \wedge \delta\text{Fail-ex}(x)$   
                        $\iota\text{Cont}(x) \leftarrow \iota\text{Sign}(x) \wedge \neg\text{Fail-ex}(x) \wedge \neg\iota\text{Fail-ex}(x)$   
                        $\iota\text{Cont}(x) \leftarrow \iota\text{Sign}(x) \wedge \delta\text{Fail-ex}(x)$   
                        $\delta\text{Cont}(x) \leftarrow \delta\text{Sign}(x) \wedge \neg\text{Fail-ex}(x)$   
                        $\delta\text{Cont}(x) \leftarrow \text{Cont}(x) \wedge \iota\text{Fail-ex}(x)$   
 T:                    $\delta\text{Fail-ex}(\text{John})$

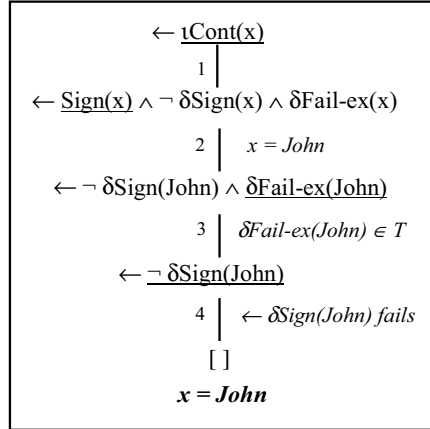


Fig. 1. Computing answers for  $\leftarrow \iota\text{Cont}(x)$

The SLDNF refutation of Figure 1 shows that  $T = \{\delta\text{Fail-ex}(\text{John})\}$  induces the insertion of  $\text{Cont}(\text{John})$ , i.e.  $\theta = \{x = \text{John}\}$ . Note that the SLDNF tree rooted at  $\leftarrow \iota\text{Cont}(x)$  succeeds with a computed answer  $x = \text{John}$ . That means that the deletion of  $\text{Fail-ex}(\text{John})$  induces an insertion of  $\text{Cont}(\text{John})$ . Selecting other rules at step 1 of this tree does not result on any other successful branch and, thus, no other insertion of  $\text{Cont}$  is induced due to  $T$ .

## 6.2 Using Abductive Procedures to Reason Abductively on the Event Rules

We show now how the Events Method (Teniente and Olivé 1995), Inoue and Sakama's method (Inoue and Sakama 1998, Inoue and Sakama 1999) and SLDNFA (Denecker and Schreye 1998) may be used to perform abductive reasoning on the event rules and, hence, to deal with schema validation and updating processing problems. Other existing procedures could have been used as well like, for instance, (Kakas and Mancarella 1990) which was the first attempt to use abduction in a database context. However, we have just considered some of the most recent proposals since they can be understood in some sense as an evolution of the initial ones.

A detailed discussion on the specific features and limitations of other (abductive) methods to perform view updating and integrity maintenance can be found in (Mayol and Teniente 1999).

### 6.2.1 The Events Method

The Events Method (Teniente and Olivé 1995) takes the event rules explicitly into account to obtain all possible minimal sets  $T_i$  on the EDB that satisfy a given update request on the IDB. It extends the SLDNF proof procedure to obtain all possible transactions  $T_i$  and it has been proved to be sound and complete for stratified databases (Teniente and Olivé 1995). Soundness of the method guarantees that the obtained transactions satisfy the update request, while completeness ensures that it obtains all minimal transactions.

In this method, an update request  $u$  is a conjunction of positive and negative events (base and derived). Positive events correspond to updates that must be effectively performed during the transition from the old state of the database to the new state, while negative events correspond to updates that may not happen during this transition.

Let  $D$  be a deductive database,  $A(D)$  its augmented database,  $u$  an update request and  $T_i$  a set of base events. In the Events Method,  $T_i$  satisfies the request  $u$  if, using SLDNF resolution, the goal  $\leftarrow u$  succeeds from input set  $A(D) \cup T_i$ . Each set  $T_i$  is obtained by having some failed SLDNF derivation of  $A(D) \cup \leftarrow u$  succeed. The possible ways in which a failed derivation may succeed correspond to the different sets  $T_i$  that satisfy the request. If no  $T_i$  is obtained, then it is not possible to satisfy the requested update by changing only the EDB.

Although the event rules define the exact difference between consecutive database states, making a failed SLDNF derivation succeed does not always guarantee the generation of minimal solutions only. Therefore, the Events Method includes also a final step to discard obtained non-minimal solutions. We must note that the Events Method may not terminate in the presence of recursive rules because it may enter into an infinite loop. Moreover, as far as efficiency is concerned, it provides certain limitations on the treatment of rules with existential variables.

Let  $u$  be an update request. In the Events Method, a transaction  $T$  satisfies  $u$  if there is a constructive derivation from  $(\leftarrow u \ \emptyset \ \emptyset)$  to  $([\ ] \ T \ C)$ . The transaction

T contains the base event facts to be applied, while the condition set C contains base events (subgoals in the general case) that would invalidate the update request if applied. A constructive derivation is defined as follows (for convenience, let G/L stand for the goal obtained from a goal G by dropping a selected occurrence of literal L in G):

*Definition 6*

A *constructive derivation* from  $(G_1 \ T_1 \ C_1)$  to  $(G_n \ T_n \ C_n)$  via a safe computation rule R (Lloyd 1987) is a sequence:

$$(G_1 \ T_1 \ C_1), (G_2 \ T_2 \ C_2), \dots, (G_n \ T_n \ C_n)$$

such that for each  $i \geq 1$ ,  $G_i$  has the form  $\leftarrow L_1 \wedge \dots \wedge L_k$ ,  $R(G_i) = L_j$  and  $(G_{i+1} \ T_{i+1} \ C_{i+1})$  is obtained according to one of the following rules:

- A1) If  $L_j$  is a positive literal and it is not a base event, then  $G_{i+1} = S$ , where S is the resolvent of some clause in  $A(D)$  with  $G_i$  on the selected literal  $L_j$ ,  $T_{i+1} = T_i$  and  $C_{i+1} = C_i$ .
- A2) If  $L_j$  is a positive base event ' $\iota P$ ' (resp. ' $\delta P$ '), there is a substitution  $\sigma$  such that  $P\sigma$  does not hold (resp.  $P\sigma$  holds) in the current database and there is a consistency derivation from  $(C_i \ T_i \cup \{L_j\sigma\} \ C_i)$  to  $(\{\} \ T' \ C')$  then  $G_{i+1} = G_i\sigma/L_j\sigma$ ,  $T_{i+1} = T'$  and  $C_{i+1} = C'$ .  
Note that if  $C_i = \emptyset$  or  $L_j\sigma \in T_i$  then  $G_{i+1} = G_i\sigma \setminus L_j\sigma$ ,  $T_{i+1} = T_i \cup \{L_j\sigma\}$  and  $C_{i+1} = C_i$ .
- A3) If  $L_j$  is negative and there is a consistency derivation from  $(\{\leftarrow \neg L_j\} \ T_i \ C_i)$  to  $(\{\} \ T' \ C')$ , then  $G_{i+1} = G_i/L_j$ ,  $T_{i+1} = T'$  and  $C_{i+1} = C'$ .

Rule A1) is an SLDNF resolution step where  $A(D)$  acts as input set. In rule A2), the selected base event is included in the transaction set  $T_i$  to get a successful derivation for the current branch, provided that the event does not violate any of the conditions in  $C_i$ . In rule A3), we get the next goal if we can ensure consistency for the selected literal.

*Definition 7*

A *consistency derivation* from  $(F_1 \ T_1 \ C_1)$  to  $(F_n \ T_n \ C_n)$  via a safe computation rule R is a sequence:

$$(F_1 \ T_1 \ C_1), (F_2 \ T_2 \ C_2), \dots, (F_n \ T_n \ C_n)$$

such that for each  $i \geq 1$ ,  $F_i$  has the form  $H_i \cup F'_i$ , where  $H_i = \leftarrow L_1 \wedge \dots \wedge L_k$  and, for some  $j=1 \dots k$ ,  $(F_{i+1} \ T_{i+1} \ C_{i+1})$  is obtained according to one of the following rules:

- B1) If  $L_j$  is a positive literal and it is not a base event, then  $F_{i+1} = S' \cup F'_i$ ,  $T_{i+1} = T_i$  and  $C_{i+1} = C_i$ ; where  $S'$  is the set of all resolvents of clauses in  $A(D)$  with  $H_i$  on the selected literal  $L_j$  and  $\not\models S'$ . Note that, if no input clause in  $A(D)$  can be unified with  $L_j$ , then  $S' = \emptyset$  and  $F_{i+1} = F'_i$ .
- B2) If  $L_j$  is a positive base event, then  $F_{i+1} = S' \cup F'_i$ ,  $T_{i+1} = T_i$  and  $C_{i+1} = C_i \cup \{H_i\}$ ; where  $S'$  is the set of all resolvents of clauses in  $T_i$  with  $H_i$  on the selected literal  $L_j$  and  $\not\models S'$ . If  $L_j$  is ground then  $C_{i+1} = C_i$ .

- B3) If  $L_j$  is a negative literal,  $\neg L_j$  is not a base event,  $k > 1$  and there is a consistency derivation from  $(\{\leftarrow \neg L_j\} T_i C_i)$  to  $(\{\} T' C')$ , then  $F_{i+1} = \{H_i \setminus L_j\} \cup F'_i$ ,  $T_{i+1} = T'$  and  $C_{i+1} = C'$ .
- B4) If  $L_j$  is a negative base event,  $\neg L_j \notin T_i$  and  $k > 1$ , then  $F_{i+1} = \{H_i \setminus L_j\} \cup F'_i$ ,  $T_{i+1} = T_i$  and  $C_{i+1} = C_i$ .
- B5) If  $L_j$  is negative, and there is a constructive derivation from  $(\{\leftarrow \neg L_j\} T_i C_i)$  to  $(\{\} T' C')$ , then  $F_{i+1} = F'_i$ ,  $T_{i+1} = T'$  and  $C_{i+1} = C'$ .

Rules B1) and B2) are SLDNF resolution steps where A(D) or T act as input set, respectively. Rules B3) and B4) allow to continue with the current branch by ensuring that the selected literal  $L_j$  is consistent with respect to  $T_i$  and  $C_i$ . In rule B5) the current branch is dropped if there exists a constructive derivation for the negation of the selected literal.

Consistency derivations do not rely on the particular order in which selection rule R selects literals, since in general, all possible ways in which a conjunction  $\leftarrow L_1 \wedge \dots \wedge L_k$  can fail should be explored. Each one may lead to a different transaction. As a result of this formulation, non-minimal solutions may be obtained. They are discarded by means of a simple procedure that rejects those that are a superset of the minimal ones.

#### Example 6

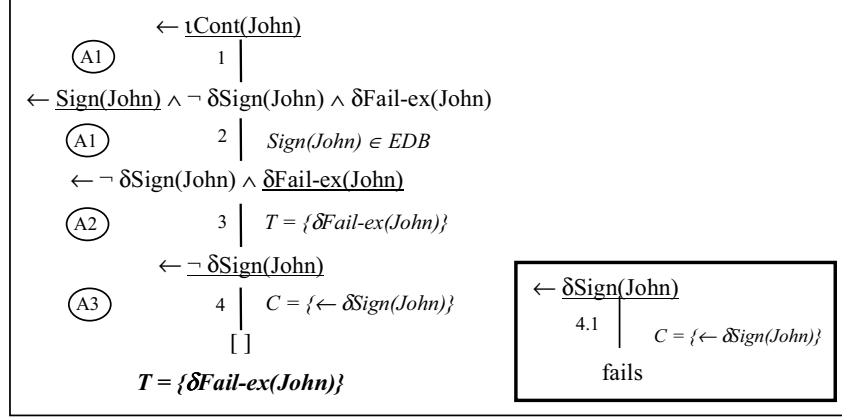
Consider again the same database as in Example 5 and assume now that the update request  $\iota\text{Cont}(\text{John})$  is requested. The corresponding abductive framework is:

$$\begin{array}{ll}
 \text{EDB} \cup \text{IDB}^*: & \text{Sign}(\text{John}) \\
 & \text{Fail-ex}(\text{John}) \\
 & \text{Cont}(x) \leftarrow \text{Sign}(x) \wedge \neg \text{Fail-ex}(x) \\
 & \iota\text{Cont}(x) \leftarrow \text{Sign}(x) \wedge \neg \delta\text{Sign}(x) \wedge \delta\text{Fail-ex}(x) \\
 & \iota\text{Cont}(x) \leftarrow \iota\text{Sign}(x) \wedge \neg \text{Fail-ex}(x) \wedge \neg \iota\text{Fail-ex}(x) \\
 & \iota\text{Cont}(x) \leftarrow \iota\text{Sign}(x) \wedge \delta\text{Fail-ex}(x) \\
 & \delta\text{Cont}(x) \leftarrow \delta\text{Sign}(x) \wedge \neg \text{Fail-ex}(x) \\
 & \delta\text{Cont}(x) \leftarrow \text{Cont}(x) \wedge \iota\text{Fail-ex}(x) \\
 \text{Ab}: & \{ \iota\text{Sign}, \delta\text{Sign}, \iota\text{Fail-ex}, \delta\text{Fail-ex} \}
 \end{array}$$

Figure 2 shows that the abductive interpretation of the event rules of Cont provided by the Events Method computes the abductive explanation  $T = \{\delta\text{Fail-ex}(\text{John})\}$  for  $\iota\text{Cont}(\text{John})$ . This is done by performing a constructive derivation rooted at  $\leftarrow \iota\text{Cont}(\text{John})$ . Circled labels appearing at the left of the derivation are references to the rules of the Events Method we have just defined.

The Events Method starts from the update request  $\leftarrow \iota\text{Cont}(\text{John})$  and uses SLDNF resolution pursuing the empty clause. Steps 1 and 2 are standard SLDNF resolution steps. At step 3, an abducible fact is selected. Then, it is included in the input set T and used as input clause if we want to get a successful derivation for  $\leftarrow \iota\text{Cont}(\text{John})$ .

Finally, at step 4, a negative base event literal is selected. Then, its corresponding subsidiary derivation must be considered, which is shown enclosed by the bold box. To ensure failure of this derivation it must be guaranteed that  $\delta\text{Sign}(\text{John})$  will

Fig. 2. Constructive derivation for  $\leftarrow \iota\text{Cont}(\text{John})$ 

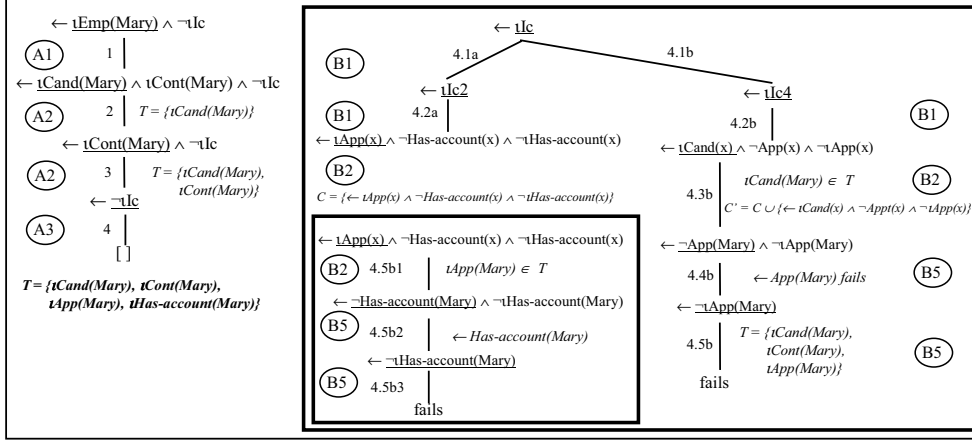
not be included into  $T$  later on during the derivation process. This is achieved by means of an auxiliary set  $C$  that contains conditions to be satisfied during the whole derivation process. These conditions correspond to some of the goals reached in subsidiary derivations, as shown at step 4.1 of Figure 2 where the condition  $\leftarrow \delta\text{Sign}(\text{John})$  is included in  $C$ . Hence, before adding a base event to  $T$  we must enforce that it does not falsify any of the conditions of  $C$ .

Once the empty clause is reached in the primary derivation, the abductive procedure finishes and  $T$  gives the base events that, applied to the EDB, will satisfy the requested update. From this derivation we have that  $T = \{\delta\text{Fail-ex}(\text{John})\}$ . Then, the request for inserting  $\text{Cont}(\text{John})$  can be achieved by deleting the fact  $\text{Fail-ex}(\text{John})$ .

#### Example 7

Consider now the database of Example 4. The abductive framework relevant to this example is:

EDB  $\cup$  IDB\*:  $\text{Sign}(\text{John})$   
 $\text{Fail-ex}(\text{John})$   
 $\text{Some-cand} \leftarrow \text{Cand}(\text{x})$   
 $\text{Emp}(\text{x}) \leftarrow \text{Cand}(\text{x}) \wedge \text{Cont}(\text{x})$   
 $\text{Cont}(\text{x}) \leftarrow \text{Sign}(\text{x}) \wedge \neg \text{Fail-ex}(\text{x})$   
 $\text{Ic2}(\text{x}) \leftarrow \text{App}(\text{x}) \wedge \neg \text{Has-account}(\text{x})$   
 $\text{Ic4}(\text{x}) \leftarrow \text{Cand}(\text{x}) \wedge \neg \text{App}(\text{x})$   
 $\text{Ic} \leftarrow \text{Ic2}(\text{x})$   
 $\text{Ic} \leftarrow \text{Ic4}(\text{x})$   
 $\iota\text{Emp}(\text{x}) \leftarrow \iota\text{Cand}(\text{x}) \wedge \iota\text{Cont}(\text{x})$   
 $\iota\text{Ic} \leftarrow \iota\text{Ic2}(\text{x})$   
 $\iota\text{Ic} \leftarrow \iota\text{Ic4}(\text{x})$   
 $\iota\text{Ic2}(\text{x}) \leftarrow \iota\text{App}(\text{x}) \wedge \neg \text{Has-account}(\text{x}) \wedge \neg \iota\text{Has-account}(\text{x})$   
 $\iota\text{Ic4}(\text{x}) \leftarrow \iota\text{Cand}(\text{x}) \wedge \neg \text{App}(\text{x}) \wedge \neg \iota\text{App}(\text{x})$   
 Ab:  $\{ \iota\text{Cand}, \delta\text{Cand}, \iota\text{Cont}, \delta\text{Cont}, \iota\text{Sign}, \delta\text{Sign}, \iota\text{Fail-ex},$

Fig. 3. Constructive derivation for  $\leftarrow \iota \text{Emp}(\text{Mary}) \wedge \neg \iota \text{Ic}$ 

$$\delta \text{Fail-ex } \iota \text{App}, \delta \text{App}, \iota \text{Has-account}, \delta \text{Has-account}\}$$

Assume that we want to insert the derived fact  $\text{Emp}(\text{Mary})$  without violating any integrity constraint. In this case, the abductive interpretation of  $\iota \text{Emp}(\text{Mary}) \wedge \neg \iota \text{Ic}$  defines the possible sets  $T_i$ ,  $\{\iota \text{Emp}(\text{Mary})\} \subseteq T_i$ , that do not induce  $\iota \text{Ic}$ . This is shown in Figure 3.

As it happens in the Example 6, the Events Method starts from the update request  $\leftarrow \iota \text{Emp}(\text{Mary}) \wedge \neg \iota \text{Ic}$  and uses SLDNF resolution pursuing the empty clause. In this case, base event facts  $\iota \text{Cand}(\text{Mary})$  and  $\iota \text{Cont}(\text{Mary})$  are included in the translation set  $T_i$  during steps 2 and 3 of the primary constructive derivation. At step 4, the subsidiary consistency derivation (enclosed by the bold box) rooted at  $\iota \text{Ic}$  must fail finitely to get the empty clause in the constructive derivation. Steps 4.1a and 4.2a of this subsidiary derivation are SLDNF resolution steps. After this step, a failed goal is reached and it is included in the condition set  $C$  to guarantee that latter additions to  $T$  do not make it succeed.

Steps 4.1b to 4.4b are SLDNF resolution steps, with the extension that the goal is included in  $C$  at step 4.3b. At step 4.5b, we have, in turn, a subsidiary constructive derivation (not shown in the previous figure) which is handled in the same way as the primary constructive one. This derivation causes the inclusion of  $\iota \text{App}(\text{Mary})$  into  $T$ . Moreover, it must be ensured that this inclusion does not violate any of the conditions in  $C$ . This is done by means of the subsidiary derivation rooted at  $\leftarrow \iota \text{App}(x) \wedge \neg \text{Has-account}(x) \wedge \neg \iota \text{Has-account}(x)$  which, in turn, requires the inclusion of  $\iota \text{Has-account}(\text{Mary})$  into  $T$  (this is done in the constructive derivation associated to step 4.5b3, which is not shown in Figure 3).

Once the empty clause is reached, the abductive procedure finishes and  $T$  contains the base events that satisfy the requested update. From this derivation we have that  $T_i = \{\iota \text{Cand}(\text{Mary}), \iota \text{Cont}(\text{Mary}), \iota \text{App}(\text{Mary}), \iota \text{Has-account}(\text{Mary})\}$ . This is the only solution that satisfies the requested update in this example.

## 6.2.2 Inoue and Sakama's Method

In this proposal (Inoue and Sakama 1998, Inoue and Sakama 1999), an abductive logic program ALP is defined as a pair  $\prec P, A \succ$  where  $P$  is a normal logic program and  $A$  is a set of abducible atoms. Given an ALP, Inoue and Sakama define a set of production rules, its *transaction program*  $\tau P$ , that declaratively specifies addition and deletion of abductive hypothesis. Abductive explanations are then computed by the fixpoint of the transaction program using a bottom-up model generation procedure.

They consider two possible kinds of explanations: positive and negative. Given an ALP  $\prec P, A \succ$  and an observation  $G$ , a set of hypothesis  $E$  is a *positive explanation* for  $G$  if  $P \cup E \models G$  and  $P \cup E$  is consistent. Similarly, a set of hypothesis  $F$  is a *negative explanation* for  $G$  if  $P \setminus F \models G$  and  $P \setminus F$  is consistent.

Moreover, they apply abduction also to “unexplain” an observation (look for antiexplanations). Given a normal logic program  $P$  and an observation  $G$ , a set of hypothesis  $E$  is a *positive anti-explanation* for  $G$  if  $P \cup E \not\models G$  and  $E$  is consistent. Similarly, a set of hypothesis  $F$  is a *negative anti-explanation* for  $G$  if  $P \setminus F \not\models G$  and  $E$  is consistent.

Their method has been shown sound and complete for covered acyclic normal logic programs. A normal logic program  $P$  is covered if, for every rule in  $P$ , all variables in the body appear in the head. In particular, this restriction does not allow having non-ground integrity constraints neither existential variables in the body of rules.

There is a clear correspondance between looking for (negative) explanations that explain/unexplain an observation and the kind of updates we can consider with the event rules. In particular, a positive explanation (anti-explanation)  $E$  is a set of event facts to be inserted (i.e. a set of base insertion events) while a negative explanation (anti-explanation)  $F$  is a set of event facts to be deleted (i.e. a set of base deletion events). Moreover, to explain an observation  $G$  that does not hold in the current database corresponds to consider the update request  $\iota G$ , to unexplain  $G$  (which holds in the current database) corresponds to consider the update request  $\delta G$ .

We may use Inoue and Sakama's method to reason abductively on the event rules. We have to:

1. Consider the ALP  $\prec P^*, A \succ$  where  $P^*$  is the augmented database of  $P$  and  $A$  is the set of base event facts (both insertion and deletion).
2. To include the following rules in the transaction program  $\tau P^*$ :
  - For each base fact  $q$  that belongs to the EDB, we have to include the rule:  $\text{in}(\iota q) \rightarrow \text{false}$ .
  - For each base fact  $q$  that does not belong to the EDB, we have to include the rule:  $\text{in}(\delta q) \rightarrow \text{false}$

These rules are needed to distinguish event predicates from database ones and to guarantee that an event can be successfully applied.

Furthermore, since events (and events facts) are handled in this way, we also require to apply rule 3 of the definition of transaction program as defined in

page 346 of (Inoue and Sakama 1999) only to base facts, and not to apply it to events facts. This rule states that for any atom  $A$  that does not appear in the head of any rule in  $P$  we must introduce the production rule  $out(A) \rightarrow \varepsilon$  and if  $A$  is not abducible we must introduce also  $in(A) \rightarrow false$ .

3. To perform abductive reasoning on a derived event fact  $\iota p$  (resp.  $\delta p$ ), we have to *explain*  $\iota p$  (resp.  $\delta p$ ). On the other hand, to perform abductive reasoning on a negative derived event fact  $\neg \iota p$  (resp.  $\neg \delta p$ ), we have to *unexplain*  $\neg \iota p$  (resp.  $\neg \delta p$ ).

As a result of applying Inoue and Sakama's method according to the previous transformations we obtain several explanations  $\prec E_i, F_i \succ$ . For each such explanation  $\prec E_i, F_i \succ$ ,  $E_i$  corresponds to the abductive explanation that satisfies the request while  $F_i$  contains base events that may not belong to  $E_i$ .

Note that the sets  $F_i$  play a similar role than the condition set in the events method. However, due to the restrictions imposed by Inoue and Sakama's method, each  $F_i$  contains only base event facts while the condition set contains more general goals.

Example 8 [adapted from example 3.2 of (Inoue and Sakama 1999)] illustrates the use of Inoue and Sakama's method to perform abductive reasoning on the event rules.

#### Example 8

Let  $\prec P, A \succ$  be an ALP where:

$$\begin{array}{ll} P: & P \leftarrow P \wedge \neg A \\ & Q \leftarrow \neg C \\ & C \leftarrow \\ A: & A, C \end{array}$$

The relevant rules of  $P^*$  are the following:

$$\begin{array}{ll} P: & \iota P \leftarrow \iota Q \wedge \neg A \wedge \neg \iota A \\ & \iota Q \leftarrow \delta C \end{array}$$

and the new abducibles atoms are  $\delta C$ ,  $\iota A$ ,  $\iota C$ ,  $\delta A$ .

Then, the subset of  $\tau P^*$  obtained for the previous rules becomes:

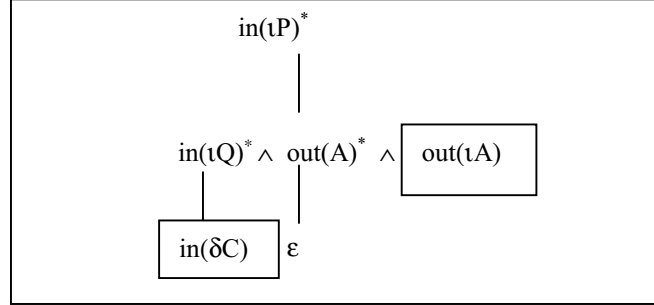
$$\begin{array}{l} in(\iota P) \rightarrow in(\iota Q) \wedge out(A) \wedge out(\iota A) \\ in(\iota Q) \rightarrow in(\delta C) \end{array}$$

Now, to perform abductive reasoning on  $\iota P$  we have to compute the explanations for  $\iota P$ . Figure 4 shows the behaviour of Inoue and Sakama's method in this case. Note that, as a result, we have obtained the minimal explanations for  $\iota P$ :  $\prec E, F \succ = \prec \{in(\delta C)\}, \{out(\iota A)\} \succ$ . That means that to insert  $P$  we should delete  $C$ .

From the previous example, we can conclude that Inoue and Sakama's method is not only applicable to the update problems they mention in (Inoue and Sakama 1998, Inoue and Sakama 1999), mainly view updating and satisfiability checking, but also to the rest of schema validation and update processing problems in covered acyclic databases.

Moreover, by explicitly considering the event rules, this method is able to perform



Fig. 4. Computing explanations for  $\leftarrow \iota P$ 

more precise requests. It is not difficult to see that in (Inoue and Sakama 1999) an anti-explanation of  $P$  takes two different cases into account: whether  $P$  is false in the old state of the database and it is not inserted during the transition and whether  $P$  is deleted during the transition. By considering events about  $P$  we can be more specific since we can just look for anti-explanations of  $\iota P$  (which corresponds only to the second case). A similar claim can be made when looking for explanations. In fact, this distinction would allow them also to be able to define and handle dynamic integrity constraints. For instance, the dynamic constraint “it may not be inserted Joan as an employee and deleted the Sales department at the same time” may be specified as:  $\leftarrow \iota \text{Emp}(\text{Joan}) \wedge \delta \text{Dept}(\text{Sales})$ .

Finally we must note that, in fact, Inoue and Sakama’s method would not need to use the event rules to obtain the solutions of Example 8. However, we believe that the use of these rules could help this method to relax the restrictions it imposes on the programs it deals with. We will see in the next section other advantages provided by the event rules when more general conditions have to be taken into account.

### 6.2.3 The SLDNFA Method

Denecker and De Schreye propose SLDNFA (Denecker and Schreye 1998), an extension of SLDNF resolution, to deal with abduction in abductive logic programs with negation. Given an abductive logic program and a query  $Q_o$  to be explained, an SLDNFA computation can be understood as a process of deriving formulas of the form  $\forall (Q_o \leftarrow \Psi)$ , where  $\Psi$  is obtained from the unsolved goals of the SLDNFA computation.

In fact, SLDNFA distinguishes two kinds of abductive solutions. A *ground abductive solution* for  $\leftarrow Q_o$  is a triple  $(\Sigma', \Delta, \theta)$  with  $\Delta$  a finite set of ground abducible atoms and  $\theta$  a substitution of the variables of  $Q_o$ , both based on the alphabet  $\Sigma'$ , such that  $P + \Delta \models \forall (\theta(Q_o))$ . Similarly, an *abductive solution* for  $\leftarrow Q_o$  wrt  $P^A$  is an open formula  $\Psi$  containing only equality and abducible predicates such that  $P^A \models \forall (Q_o \leftarrow \Psi)$  and  $\exists(\Psi)$  is satisfiable wrt  $P^A$ . A ground abductive solution

can be considered as a special case of an abductive solution since many ground abductive solutions can be drawn from  $\Psi$ , in general.

SLDNFA has been proved to be sound and complete for failure. Soundness ensures that the obtained solutions are correct since they entail the initial query and are consistent. Completeness for failure guarantees that if there exists a failed SLDNFA-tree for an initial query, then the query has no abductive solutions. However, this does not imply that SLDNFA generates all ground abductive solutions or all ground solutions satisfying some minimality criteria, as already pointed out by Denecker and De Schreye (Denecker and Schreye 1998), page 138. Two variants of SLDNFA, namely  $\text{SLDNF}^o$  and  $\text{SLDNFA}_+$ , are defined for which stronger completeness results are proved.

SLDNFA can also be used to perform abductive reasoning on the event rules. To do it, we should first rewrite event and transition rules to guarantee that they explicitly state the event definition and, thus, that the events are correctly handled by SLDNFA. That is, for each event literal  $\iota Q(x)$  appearing in the body of an event or transition rule we should add the literal  $\neg Q(x)$  to that rule, while for each event literal  $\delta Q(x)$  we should add the literal  $Q(x)$ . This rewriting is equivalent to the addition of new rules in Inoue and Sakama's method to guarantee that an event can be successfully applied.

Then, we should take the Augmented Database (corresponding to the rewritten rules) as the abductive logic program  $P^A$  where SLDNFA is applied and consider base event predicates as the only abducible predicates.

Denecker and De Schreye already mention the applicability of SLDNFA (and its variants) to other problems and, in particular, to satisfiability checking. From the use of SLDNFA to perform abductive reasoning on the event rules, we can conclude that SLDNFA is also applicable to the rest of schema validation and update processing problems. Furthermore, dynamic integrity constraints can be easily specified by means of event and transition rules and, thus, they could also be handled by SLDNFA.

Example 9 [a simplified version of the example in p.119 of (Denecker and Schreye 1998)] illustrates the use of SLDNFA to perform abductive reasoning on the event rules.

#### Example 9

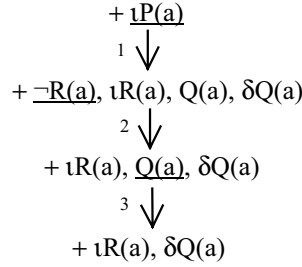
Consider the following deductive database:

$$\begin{aligned} & Q(a) \\ & P(x) \leftarrow R(x) \wedge \neg Q(x) \end{aligned}$$

The abductive logic program  $P^A$  corresponding to the previous database is:

$$\begin{aligned} (I.1) \quad & \iota P(x) \leftarrow R(x) \wedge \neg \delta R(x) \wedge Q(x) \wedge \neg \delta Q(x) \\ (I.2) \quad & \iota P(x) \leftarrow \neg R(x) \wedge \iota R(x) \wedge \neg Q(x) \wedge \neg \iota Q(x) \\ (I.3) \quad & \iota P(x) \leftarrow \neg R(x) \wedge \iota R(x) \wedge Q(x) \wedge \delta Q(x) \\ \text{Abducibles:} \quad & \{ \iota R, \delta R, \iota Q, \delta Q \} \end{aligned}$$

An SLDNFA-refutation to find abductive solutions for  $\iota P(a)$  (which corresponds to the initial query  $\leftarrow \iota P(a)$ ) is shown in Figure 5. The ground abductive answer

Fig. 5. SLDNFA-refutation for  $\leftarrow \iota P(a)$ 

generated by this refutation is  $(\Sigma, \{\iota R(a), \delta Q(a)\}, \varepsilon)$ . This answer states that the insertion of  $P(a)$  may be achieved by the insertion of  $R(a)$  and the deletion of  $Q(a)$ .

The use of the event rules provides also other contributions to SLDNFA. For instance, it allows SLDNFA to obtain solutions that would not be generated otherwise. For instance, SLDNFA (as defined in (Denecker and Schreye 1998)) would not obtain any solution to the request insert  $P(a)$  in Example 9. The reason is that SLDNFA considers only positive explanations, but no negative explanations (according to the terminology of Inoue and Sakama (Inoue and Sakama 1999)). Therefore, it can not generate the deletion of  $Q(a)$  which is required to insert  $P(a)$ . We have shown in Figure 5 that the use of the event rules allows SLDNFA to obtain such kind of solutions since abducting events corresponds always to the generation of positive explanations although an event may correspond to a deletion of a database atom.

Another limitation that is overcome by the use of the event rules is that a direct application of SLDNFA to integrity constraint maintenance is not incremental. That is, it does not exploit the fact that the old database satisfies the integrity constraints, but rechecks blindly all of them (Denecker and Schreye 1998) (page 158). Again, such situation can also be overcome if SLDNFA is used in conjunction with the event rules, as shown in Example 10.

#### Example 10

Consider the following deductive database:

$$\begin{array}{l}
Q(b) \ R(b) \ Q(c) \ R(c) \ Q(d) \ R(d) \\
Ic \leftarrow Q(x) \wedge \neg R(x)
\end{array}$$

The abductive logic program corresponding to the previous database is:

$$\begin{array}{ll}
(I.1) & \iota Ic \leftarrow Q(x) \wedge \neg \delta Q(x) \wedge R(x) \wedge \neg \delta R(x) \\
(I.2) & \iota Ic \leftarrow \neg Q(x) \wedge \iota Q(x) \wedge \neg R(x) \wedge \neg \iota R(x) \\
(I.3) & \iota Ic \leftarrow \neg Q(x) \wedge \iota Q(x) \wedge R(x) \wedge \delta R(x) \\
\text{Abducibles:} & \{ \iota Q, \delta Q, \iota R, \delta R \}
\end{array}$$

An SLDNFA-refutation to find abductive solutions for  $\iota Q(a)$  that do not violate

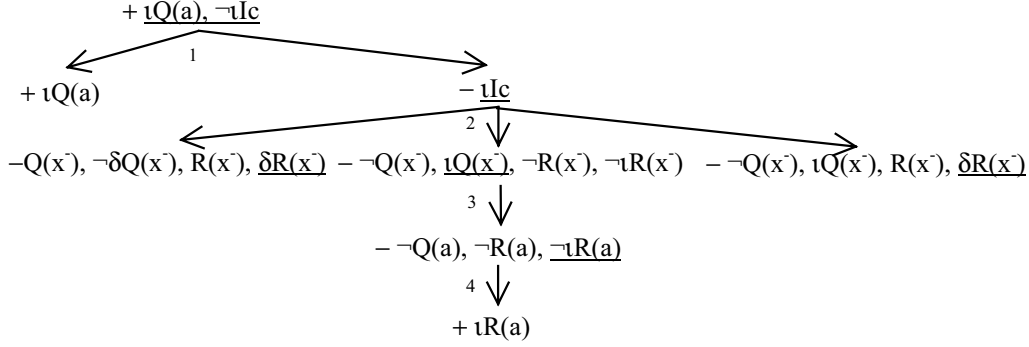


Fig. 6. SLDNFA-refutation for  $\leftarrow \iota Q(a) \wedge \neg \iota I_c$

integrity constraints (which corresponds to the initial query  $\leftarrow \iota Q(a) \wedge \neg \iota I_c$ ) is shown in Figure 6.

The ground abductive answer generated by this refutation is  $(\Sigma, \{\iota Q(a), \iota R(a)\}, \varepsilon)$ . Note that, in this case, integrity constraint maintenance has taken into account that integrity constraints are satisfied before the update since it has only considered the events that could induce a violation of  $I_c$  (and not all database facts involved in the definition of  $I_c$ , as SLDNFA would do in the absence of the event rules).

#### 6.2.4 How many Methods do we really need to deal with Database Problems?

In general, research related to database problems is still looking for methods able to deal only with specific problems. However, we have shown that all problems are either of abductive or deductive nature and, thus, they can be formulated in terms of just two forms of reasoning. Therefore, we may conclude from our results that at most two different procedures are enough to handle all of them.

In fact, it could also be argued that just one single general procedure would be enough since it has been shown that either abduction as well as deduction can be realized in terms of the other. For instance, (Bry 1990, F.Bry, Eisinger, Schütz and Torge 1998) have proposed a procedure that allows to perform abductive reasoning by means of deduction, while (Denecker and Schreye 1998, Inoue and Sakama 1999) have shown that their abductive procedures can also be used for deduction. Clearly, this strengthens our claim that we do not need a different method to deal with each schema validation and update processing problem.

The discussion about whether it would be better to have just one single method or two is far beyond the scope of this paper since it requires to be further investigated. From our intuition, we think that it will be difficult to define a single method which is as efficient to perform abductive reasoning as it is to perform deductive reasoning since, as we have shown in the paper, the nature of the corresponding problems is intrinsically abductive or deductive. In this sense, we believe that it is difficult to incorporate the optimizations required to efficiently deal with deductive problems

into a method based on abductive reasoning (and the other way around). However, this is still an open problem and it is a challenger research.

## 7 Using the Event Rules to Perform General Abductive Reasoning

We have shown how the event rules can be used to deal with several schema validation and update processing problems and we have illustrated how several deductive and abductive procedures can be used to reason on them. In this section, we sketch how the event rules can be used also to solve general abductive problems in addition to the database problems considered before. Obviously, we must take into account that whenever we use the event rules we obtain solutions that minimize the difference between the old and the new states and that this is not necessarily a requirement that the abductive explanations must satisfy in general.

We illustrate, by means of the following example, how could we use the event rules to deal with a typical abductive task like fault diagnosis and how the expected solutions to this problem can be abduced from these rules.

### Example 11

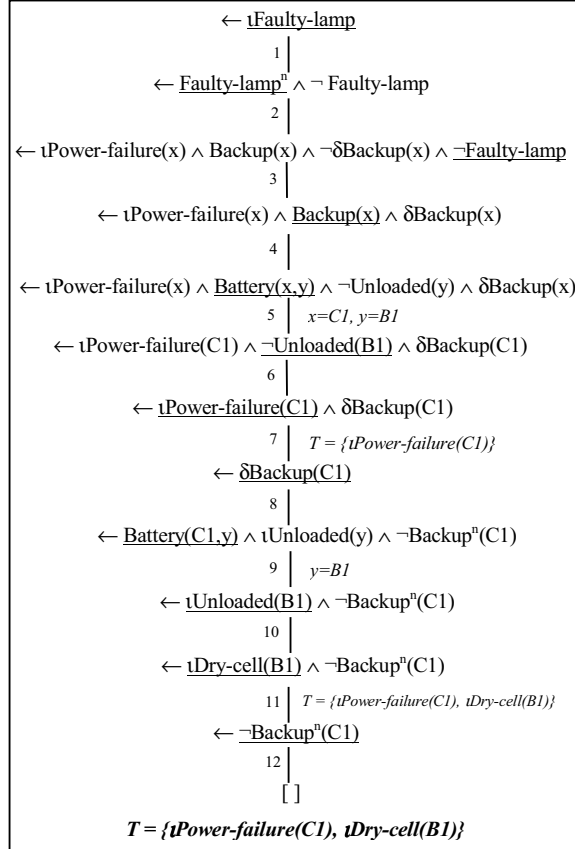
The relevant part of the abductive framework of this example is the following:

EDB  $\cup$  IDB\*: Lamp(L1)  
 Battery(C1,B1)  
 Faulty-lamp  $\leftarrow$  Lamp(x)  $\wedge$  Broken(x)  
 Backup(x)  $\leftarrow$  Battery(x,y)  $\wedge$   $\neg$ Unloaded(y)  
 Faulty-lamp  $\leftarrow$  Power-failure(x)  $\wedge$   $\neg$ Backup(x)  
 Unloaded(x)  $\leftarrow$  Dry-cell(x)  
 $\iota$ Faulty-lamp  $\leftarrow$  Faulty-lamp<sup>n</sup>  $\wedge$   $\neg$ Faulty-lamp  
 Faulty-lamp<sup>n</sup>  $\leftarrow$   $\iota$ Power-failure(x)  $\wedge$  Backup(x)  $\wedge$   $\delta$ Backup(x)  
 Faulty-lamp<sup>n</sup>  $\leftarrow$   $\iota$ Power-failure(x)  $\wedge$   $\neg$ Backup(x)  $\wedge$   $\neg \iota$ Backup(x)  
 Faulty-lamp<sup>n</sup>  $\leftarrow$  Lamp(x)  $\wedge$   $\neg \delta$ Lamp(x)  $\wedge$   $\iota$ Broken(x)  
 $\delta$ Backup(x)  $\leftarrow$  Battery(x,y)  $\wedge$   $\iota$ Unloaded(y)  $\wedge$  Backup<sup>n</sup>(x)  
 $\iota$ Unloaded(x)  $\leftarrow$   $\iota$ Dry-cell(x)  
 Ab: {  $\iota$ Broken,  $\delta$ Broken,  $\iota$ Power-failure,  $\delta$ Power-failure,  $\iota$ Dry-cell,  $\delta$ Dry-cell }

Within this framework, we can use the event rules to detect that a faulty lamp problem is caused by a broken lamp or by a power failure of a circuit without backup, that is, a loaded battery. To do it, we have selected the Events Method among the three possible abductive procedures considered in Section 6.2.

Figure 7 shows how, given the goal  $\leftarrow \iota$ Faulty-lamp and EDB  $\cup$  IDB\*, the Events Method obtains the abductive solution  $T = \{\iota$ Power-failure(C1),  $\iota$ Dry-cell(B1)  $\}$ , which is a possible solution for having a faulty lamp.

The Events Method would also obtain the solution  $T = \{\iota$ Broken(L1)  $\}$  by considering the rule  $\text{Faulty-lamp}^n(x) \leftarrow \text{Lamp}(x) \wedge \delta \text{Lamp}(x) \wedge \iota \text{Broken}(x)$  at step 2 of Figure 7, and other possible solutions, like for instance  $T = \{\iota$ Power-failure(C2)  $\}$ , by considering the rule  $\text{Faulty-lamp}^n(x) \leftarrow \iota \text{Power-failure}(x) \wedge \text{Backup}(x) \wedge \neg \iota \text{Backup}(x)$  also at step 2. The resulting derivations are not shown in the tree above.

Fig. 7. Constructive derivation for  $\leftarrow \iota\text{Faulty-lamp}$ 

## 8 Conclusions and Further Work

We have shown that database schema validation and update processing problems can be classified into problems of either deductive or abductive nature according to the reasoning paradigm that is more adequate to solve them. This has been done by making explicit the exact changes that occur in a transition between two consecutive states of the database by means of the event rules (Olivé 1991) and by performing deductive and abductive reasoning on these rules. In this way, we have distinguished between *deductive problems*, concerned with computing the changes on derived predicates induced by a transaction, and *abductive problems*, concerned with determining the possible transactions that satisfy a set of changes on derived predicates. We have also shown that deductive and abductive problems can be combined, thus defining more complex update problems.

Thus, problems like materialized view maintenance, integrity constraint checking or condition monitoring are considered as naturally deductive, while problems like view updating, integrity constraint maintenance or enforcing condition activation as naturally abductive.

By taking only a unique set of rules and two forms of reasoning into account to specify and deal with all these problems, we have shown that it is possible to provide general methods able to uniformly deal with several database updating problems at the same time. This suggests that future research in this field should be aimed at providing general methods instead of proposing specific methods for solving a particular problem like has been traditionally done in the past. Moreover, all these problems could be uniformly integrated into a database update processing system.

We have also shown how some existing general deductive and abductive procedures may be used to reason on the event rules. In this way, we have shown that these procedures can be used to deal with all database problems considered in this paper. This has been illustrated by means of examples and some additional benefits gained by these procedures when reasoning on the event rules have also been pointed out. Moreover, we have sketched how the event rules could be used to solve general abductive problems in addition to database schema validation and update processing problems.

The results presented in this paper may be extended at least in three different directions. First, our framework could be generalized to databases that allow recursive rules. Second, to deepen in the study of the application of the event rules to current abductive procedures to provide an efficient implementation of abductive reasoning on the event rules. Third, the advantages and inconveniencies of using the event rules to perform general abductive reasoning should be further investigated.

### Acknowledgements

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