The Basic Query Machine of the KIWIS system‡

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Abstract. KIWIS is an advanced environment for large database systems which supports knowledge-based applications and provides a seamless integration of information coming from different external sources. The system relies on a new knowledge representation and manipulation language, called LOCO, that is based on a tight integration between the object-oriented and the logic programming paradigm. The implementation of LOCO is supported both by a top-down and a bottom-up executor, allowing great flexibility and suitability for large knowledge based applications. This paper describes the basic implementation principles as well as the integrated architecture of the Basic Query Machine (BQM) - the module of KIWIS in charge of implementing the bottom-up model of execution of a class of LOCO programs. The structure of such programs (called *stratified*), amenable of an efficient bottom-up evaluation even in case of data intensive applications, is discussed in details. The mechanism for a strict cooperation with the top-down evaluator, is also presented.

1. Introduction

KIWIS is an advanced environment for large database systems which supports knowledge-based applications and provides a seamless integration of information coming from different external sources ([KIWIS89,VL90,Ahl91]).

The system relies on a new knowledge representation and manipulation language, called LOCO [LVVS90], that is based on a tight integration between the object-oriented and the logic programming paradigm. In addition, the language supports features such as defeasible and default reasoning, making it suitable also for AI-flavored applications (e.g. expert systems).

The overall architecture of the system is shown in Figure 1.1.

The *Abstraction Layer* (AL) and the *Basic Query Machine* (BQM) [LMRR91] provides the necessary support for the native KIWIS language, LOCO, by implementing respectively backward (top-down) and forward (bottom-up) chaining. The rationale of having two different execution strategies is twofold: the bottom-up engine ensures the proper termination of fully declarative LOCO programs, granting an efficient execution also with large amount of data; on the other hand, the top-down evaluator supports the execution of general LOCO programs (even if termination is not granted), including updates, metaprogramming and extra-logical predicates. Thus, the coexistence of top-down and bottom-up engines becomes one of the relevant features of the KIWIS system, allowing great flexibility, suitability for large knowledge based

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Figure 1.1: Overall KIWIS Architecture

applications.

Both AL and BQM can rely on the *Object Virtual Machine* (OVM) for the efficient management of complex objects both in main and secondary memory. On the other hand, based on the AL and BQM services, the *User Interface Development System* (UIDS) supports customizable views on the data together with several interaction paradigms of increasing complexity [SLT90,STVDT91].

Finally, two kinds of "hooks" to external information sources represent a valuable channel for the import, export, and (re-)usage of existing data.

In one case, the *External System Interface* (ESI) provides an extendible, read-only interface to a variety of external information sources (e.g. traditional, text or picture databases and applications, possibly residing on remote systems). Alternatively, the *Cooperation Manager* (CM) allows to define KIWIS as a federation [AJ90] of loosely coupled (KIWIS) knowledge bases, to form a network for information sharing and cooperation without a commitment to a centrally maintained global schema.

The aim of this paper is to describe the design of the BQM (as bottom-up machine) and its interaction with the AL (as top-down machine). We start, in the next Section, with an informal description of the query capabilities supported by LOCO. Then, Section 3 presents the BQM language, i.e. a class of LOCO programs (indicated as *stratified*) that are amenable of an efficient bottom-up evaluation. Finally, Section 4 illustrates the relevant aspects of the actual BQM architecture. For details on some basic implementation principles, the reader is referred to the Appendices.

2. Language Overview

This section gives an informal presentation of the main features of a (fully declarative) subset of the LOCO language.

As already pointed out, LOCO is a fresh attempt of enhancing the logic programming paradigm with some of the most relevant Object Oriented (OO) features [LVVS90]. From the deductive approach, LOCO maintains a clearly defined semantics along with declarative query capabilities. On the other hand, from the OO field, the notions of object identity, structured object, and (multiple) inheritance are formally accommodated into the language as first class features. On top of this, non-monotonic and default reasoning are introduced in the language following some recent proposals [GL90,GS90,KS90,LSV90] on negative logic programs (i.e. allowing negation in the head of rules).

The language presented here, that we call *Extended Ordered Logic (EOL)*, fully captures the query capabilities of the LOCO language and is a direct evolution of the *Ordered Logic (OL)* programming. The main extension of EOL with respect to OL boils down to a sort of message passing mechanism. More formal and detailed discussions about OL can be found in [LSV90,LV90,Lae90,LR91].

As a very basic starting point, an EOL program consists of a number of *objects*, each one identified by a (unique) name and composed of a set of rules possibly with negative head literals. We briefly recall that a rule is a statement of the form $L_0 \leftarrow L_1, \dots, L_n$, where $L_0, L_1, \dots, L_n$ are literals. L_0 is the *head literal* while the set of literals $L_1, \dots, L_n$ constitutes the *body* of the rule. A rule with an empty body is also called *fact*. A positive (negative) literal has the format $p(X)$ ($\neg p(X)$) where X is a list of arguments and p ($\neg p$) is a literal symbol. We will often denote simply by p a generic literal symbol, either positive or negative.

Example 2.1. (*objects*)

```
fred = { name("Fred").
         married :- wife(X).
         wife(sally). }
```

fred, is the object identifier; the literal symbols *name*, *married*, and *wife* are used to define the properties of *fred*. In particular, the facts *name*("Fred"), and *wife*(sally) hold along with the property *married* which is inferred by the rule *married* :- *wife*(X). No negative literals appear in *fred*. $\square$

In short, an object is a logical theory or, mainly according to personal taste and background, one might imagine facts and rules instead of, e.g., instance variables and methods, respectively. In the above example, *name* could be seen as an instance variable whose value is *Fred*, and *married* as a boolean instance variable. Further, the rule *married* :- *wife*(X) might represent a method for 'computing' the property *married*.

Inheritance is a central characteristic of the EOL language. The knowledge of an object is not confined exclusively to its own rules: a simple and general specificity relation (sub/super-object) is used to model how rules filter down from one object to another.

Example 2.2. (*inheritance*) Consider the following program, where *fred* is now a sub-object of *person*. (Note: each object is preceded by the list of its immediate super-objects).

```

      person = { married :- wife(Y).
(person)  fred = { wife(sally).
                  name("Fred"). }

```

It should be intuitively clear that the properties of *fred* have not changed from the previous example. The rule for *married* is inherited from *person* so that *married* can be inferred for *fred*. On the other hand, no property holds for *person* as it misses the necessary facts for any valid inference. $\square$

Concluding, each object has its own perception of the knowledge base, given by its local rules plus some *global* rules, that is, those of the objects that are connected to it via the sub-object links. However, it is possible for an object, to refer explicitly to the properties of another object. This is achieved by allowing, within rules' bodies, *extended literals* of the form $X.p$, where X is either an object identifier or a variable and p is a literal. Intuitively, an extended literal $X.p$ should be read as " p is true at object X " or "the property p of the object X ".

Example 2.3. (*extended literals*)

```

      fred = { wife(sally).
               child(john). }
      sally = { husband(fred).
               child(X) :- husband(Y), Y.child(X). }
      john = { }

```

The program describes a married couple, *fred* and *sally*, with only one child, *john*. Instead of declaring explicitly *john* as *sally*'s child, we use a rule with an extended literal. The rule $child(X) :- husband(Y), Y.child(X)$. says that for each husband Y of *sally*, the child X of Y is also a child of *sally*. Thus, since $husband(fred)$ holds in *sally* and $child(john)$ is true at object *fred*, it is possible to infer $child(john)$ for *sally*. $\square$

Notice how the extended literals mimic the message passing mechanism of object-oriented languages; indeed, $Y.child(X)$ can be seen as a message to all Y objects, asking for the value of the *child* property. Consistently, a query to an EOL program is an extended literal, e.g. $sally.child(X)$ asks for all X values of the *child* property for *sally*.

Let us now turn our attention to the treatment of contradictions. As we shall see, contradictions are mastered by two simple rules, namely *overruling* and *defeating*, driven by the relationships between the involved objects.

Example 2.4. (*overruling*)

```

      person      = { taxPayer. }
(person)  unemployed = { ¬taxPayer. }
(unemployed) tom      = { }
(person)  john       = { }

```

The property *taxPayer* acts as a "default": it is visible from all *person*'s sub-objects and it holds unless explicitly contradicted. In fact, *taxPayer* is true for *person* and for *john*. On the contrary, only the property $\neg taxPayer$ holds for *tom* and *unemployed*, and the property *taxPayer* is rejected or, as we say, *overruled*. The rationale

of such a preference rule is that more specific information is certainly more reliable than inherited, more general properties. $\square$

Unlikely the situation above, where the ordering between the involved objects suggests an intuitive solution to contradiction handling, there are many real-world situations that are intrinsically ambiguous. The well known *Nixon Diamond* example [Tou86], shown next, illustrates a case of ambiguity coming from the multiple inheritance.

Example 2.5. (*defeating*)

$$\begin{aligned} quaker &= \{ pacifist. \} \\ republican &= \{ \neg pacifist. \} \\ (quaker \text{ } republican) \text{ } nixon &= \{ \} \end{aligned}$$

The program states: quakers are pacifist, republicans are not pacifist, nixon is both a quaker and a republican. Now, consider the question: is nixon a pacifist? There is no correlation between *republican* and *quaker* and, actually, no indication of which point of view should be thrust: the network is perfectly ambiguous and both conclusions are rejected or, as we say, *defeated*. $\square$

The above examples can be exploited for a further comment on the sub/super-object relation. As a matter of fact, it turns out that such a relation is able to capture both classification and generalization hierarchies. For instance, in the Example 2.4 the objects *person* and *unemployed* could be viewed as a sort of class objects, whereas *john* and *tom* constitute the class population of resp. *person* and *unemployed*; hence, *tom* could be considered an *instance-of unemployed*, while *unemployed IS-A person*.

It is worth noting that the language actually supports true negation instead of negation by failure, i.e., a negative fact can be inferred only if explicitly derived by a rule of the program, so that any negative information is as much valuable as a positive one.

Example 2.4. (*true negation*)

$$\begin{aligned} person &= \{ taxPayer. \} \\ (person) \text{ } tom &= \{ \neg taxPayer :- \neg rich. \} \end{aligned}$$

The meaning of this program is that *tom* is a *taxPayer*. The reason is that the failure to prove *rich* is not sufficient to infer $\neg rich$ and, consequently, $\neg taxPayer$. $\square$

3. Stratified programs

For clarity's sake, in this section we restrict ourselves to EOL programs where no extended literal appears. Such programs are known in literature as Ordered Logic programs [LSV90, LV90, Lae90, LR91] (OL programs, for short). Then, we single out a meaningful class of OL programs, that we call *stratified programs*. The extension of the notion of stratified program to cope with the presence of extended literals is rather immediate and it is discussed in Appendix 1.

A formal semantics for OL, based on an extension of the well-founded semantics of traditional logic programming [VGRS88], has been defined in [LMRR91, LR91]. In

particular, a bottom-up model of computation of such a semantics is given as a suitable adaptation of the algorithm presented in [Van89] for classical logic programs. Unfortunately, as in that case, it turns out that the computation of the well-founded model is quite demanding.

It is possible, however, to specialize the general method and make it very efficient for a meaningful class of programs, called stratified OL programs ([LMRR91, LR91]).

Typically, a stratified program shows a two-level structure: the definition of a property belongs to a certain object, while the exceptions (i.e. conflicting rules) belong only to its subobjects. In a sense, the notion of stratification can be intended as a way to detect when an OL program has a simple structure w.r.t. the treatment of contradiction so that its well-founded model can be computed in a monotonic fashion.

We illustrate the basic intuition by an example.

Example 3.1.

	<i>person</i>	= { <i>taxPayer</i> . }
(<i>person</i>)	<i>unemployed</i>	= { $\neg$ <i>taxPayer</i> :- $\neg$ <i>rich</i> . }
(<i>unemployed</i>)	<i>tom</i>	= { $\neg$ <i>rich</i> . }
(<i>person</i>)	<i>john</i>	= { }

The evaluation of *tom*'s properties could proceed as follows: first, we derive the fact $\neg$ *rich*; then we infer $\neg$ *taxPayer* from the rule $\neg$ *taxPayer* :- $\neg$ *rich*. defined in *unemployed*. Thereafter, *taxPayer* is derived through the rule in *person*, but, since $\neg$ *taxPayer* has already been inferred, *taxPayer* is discarded. Actually, $\neg$ *taxPayer*, and $\neg$ *rich*. are the only facts holding for *tom* (they are the *well-founded* model for *tom*). The reason why this approach works correctly in this case is that the above OL program has a syntactic structure ensuring the existence of a bottom-up rule evaluation ordering that preserves the "precedence" of more specific over more general rules (e.g. the precedence of the rule $\neg$ *taxPayer* :- $\neg$ *rich*. w.r.t. *taxPayer*.). Thus, we say that the program for *tom* is stratified. $\square$

Now, let P_o denote the set of rules defined at o and all its superobjects: this corresponds to the program visible by the object o . Given two literal symbols q_1 , and q_2 appearing in P_o , we say that q_1 *depends-on* q_2 , denoted by (q_1, q_2) , if either:

- 1) q_2 appears in the body of a rule for q_1 , or
- 2) q_1 and q_2 are complementary literal symbols¹, defined by rules r_1 and r_2 (resp.), and $o_{def}(r_1)$ is not a sub-object of $o_{def}(r_2)$.

where $o_{def}(r)$ denotes the object where r appears.

Example 3.2. The program P_{tom} of example 3.1 is composed by the following rules:
taxPayer. $\neg$ *taxPayer* :- $\neg$ *rich*. $\neg$ *rich*.

The depends-on relation for such a program gives $(\neg$ *taxPayer*, $\neg$ *rich*) by condition 1), and $(\textit{taxPayer}, \neg$ *taxPayer*) by condition 2), as $o_{def}(\textit{taxPayer}.) = \textit{person}$ is not a sub-object of $o_{def}(\neg$ *taxPayer* :- $\neg$ *rich*) = *unemployed*.

¹ i.e., either $q_1 = \neg q_2$ or $q_2 = \neg q_1$.

Let us now consider the program P_{nixon} of example 2.5. The depends-on relation gives: $(\neg pacifist, pacifist)$ and $(pacifist, \neg pacifist)$ as *quaker* is not a sub-object of *republican* and viceversa. $\square$

At this point we can give the definition of *dependency graph* for an object o . Given the program P_o for o , the associated *dependency graph* DG_o is a directed graph such that: i) the nodes are the literal symbols appearing in P_o , and ii) there is an arc from node q_1 to q_2 iff q_1 depends-on q_2 .

Figure 3.1 shows the dependency graphs for the objects *tom* of Example 3.1, and *nixon* of Example 2.5.

Figure 3.1: DG_{tom} and DG_{nixon}

Hence, the dependency graph associated to an object o is a compact representation of the KB, as it is perceived by o . Now, let us denote by $DG_{o,p}$ the subgraph of DG_o that consists of the node p and all nodes that are reachable from p (in DG_o). We denote by $P_{o,p}$ the program consisting of all rules (of P_o) whose head literals label the nodes of $DG_{o,p}$. Thus, a program $P_{o,p}$ is *stratified* if no cycle of $DG_{o,p}$ contains two complementary literal symbols.

Example 3.4 Consider the following program:

$$\begin{aligned} person &= \{ taxPayer. \\ &\quad citizen :- taxPayer. \\ &\quad \neg citizen :- alien. \} \\ (person) \quad unemployed &= \{ \neg taxPayer :- \neg rich. \} \\ (unemployed) \quad tom &= \{ \neg rich. \} \end{aligned}$$

The dependency graph DG_{tom} is shown in Figure 3.2. Notice that the program $P_{tom, taxPayer}$ is stratified, while $P_{tom, citizen}$ is not, as the graph $DG_{tom, citizen}$ (which is equal to DG_{tom}) contains a cycle with two complementary literal symbols, namely *citizen* and $\neg citizen$. $\square$

We are now ready to single out a convenient evaluation order of the rules of a stratified program, by devising a total ordering called *stratification*.

Given $DG_{o,p}$, let us build a new, cycle-free graph $\overline{DG}_{o,p}$ obtained by collapsing each strongly connected components of $DG_{o,p}$ into a single node of $\overline{DG}_{o,p}$ ². There exists a topological sort $\langle C_1, \dots, C_n \rangle$ of the nodes of $\overline{DG}_{o,p}$ (i.e., such that if there is

² accordingly, there is an arc (C_i, C_j) in $\overline{DG}_{o,p}$ if there exists at least an arc (n_i, n_j) in $DG_{o,p}$ where $n_i \in C_i$ and $n_j \in C_j$.

Figure 3.2: DG_{tom}

an arc from C_i to C_j in $\overline{DG}_{o,p}$, then $i < j$), that induces a totally ordered partition $S = \langle S_n, \dots, S_1 \rangle$ of $P_{o,p}$, where S_i is the set of rules whose head literal symbols are in C_i .

Given a stratified program $P_{o,p}$, the partition S is called *stratification* and each S_i is a *stratum*.

The notion of stratification is crucial for the bottom-up evaluation of a program $P_{o,p}$. Indeed, as in traditional logic programming, the process proceeds (bottom-up) from the "lower" strata to the "upper" ones. The facts that are derived for a stratum S_i are used as input data for any stratum S_j such that $i < j$. In addition, contradictions can be easily solved taking into account that literals derived from "lower" strata are more reliable. In fact, since in a stratified program rules with complementary head literal symbols appear in different strata, we are guaranteed that while solving a rule for $o.p$, either (i) no rule for $\neg p$ appears in $P_{o,p}$, as $o.p$ does not depend on $o.\neg p$; or (ii) all rules for $o.\neg p$ have been already solved as they are in "lower" strata. Hence, contradictions can be solved by simple set difference.

The *stratified naive algorithm* for OL programs is shown in Figure 3.3

Example 3.5 A stratification for $P_{tom.taxPayer}$ is $\langle \{\neg rich.\}, \{\neg taxPayer :- \neg rich.\}, \{taxPayer.\} \rangle$. Given such a stratification, the stratified algorithm follows the computation order intuitively shown in example 3.1. $\square$

4. BQM Architecture

As mentioned in the introduction, the Abstraction Layer provides a top-down evaluation of general LOCO programs. However, the actual execution is supported by a dedicated Warren Abstract Machine. Hence, to this respect, the main task of the AL is to translate a LOCO program into a persistent description of the objects, generate WAM code realizing the application, and manage the WAM execution.

The BQM, in turn, is devoted to the bottom-up evaluation of a meaningful class of LOCO programs, that we called stratified. The general framework in which AL and BQM interact is shown in Figure 4.1: whenever a stratified (sub)query is found during the top-down WAM evaluation of a query, the BQM is invoked for its bottom-up execution. The result of such a computation is then returned (one tuple at-a-time) to the WAM.

Two main distinct blocks constitute the BQM architecture: the *Static Compiler* and the *Run-Time Environment*, interfaced through the *BQM Metaschema*. Given that

The Stratified Naive Algorithm

INPUT: a query $o.p(\bar{X})$ and a stratification $\langle S_1, \dots, S_n \rangle$ for the program $P_{o.p}$

OUTPUT: the answer to the query

METHOD: the algorithm computes ordinately the fix-point of every stratum S_i by means of the functions *fixPoint* and *evalRules*.

```

function fixPoint( $S_i, I$ )
  begin
    repeat
       $\bar{I} := I$ ;
       $I := \text{evalRules}(S_i, \bar{I})$ ;
    until  $I = \bar{I}$ ;
    return( $I$ );
  end;

function evalRules( $\{r_1, \dots, r_m\}, I$ )
  begin
    for each rule  $r_i$  do
      let  $o'.p'(t)$  be derived by  $r_i$  with the facts available in  $I$ 
      if  $I$  does not contain the complementary of  $o'.p'(t)$  then
         $I := I \cup \{o'.p'(t)\}$ ;
    end
    return( $I$ );
  end;

begin {main}
   $I := \emptyset$ ;
  for  $i:=1$  to  $n$  do
     $I := \text{fixPoint}(S_i, I)$ ;
  return( $\{o.p(t) \in I \text{ s.t. unifies with } o.p(\bar{X})\}$ );
end.

```

Figure 3.3

most of the intensional information (clauses, classes, etc) is rather stable, the aim of the static analysis is to provide the run time environment with a suitably compact representation of such a knowledge. In particular — given the information gathered by the AL compiler into the *AL metaschema* (i.e. classes' hierarchy, clauses, rules, etc.) — the Static Compiler recognizes all stratified programs and stores in the BQM metaschema the result of its compilation.

The BQM Metaschema is the natural interface between the Static and the Run-Time Environment: it is constructed by the former and consulted by the latter. The main goal of the Metaschema design has been to allow a straightforward retrieval of

Figure 4.1: Architecture of the Basic Query Machine

programs and their stratifications.

The BQM Run-Time Environment is automatically and transparently activated by the WAM for each query on a stratified program. By using the BQM and AL Metaschema, it retrieves the LOCO program, produces an equivalent flat DATALOG program, and performs an optimized bottom-up evaluation. The crucial advantage of such a choice is that it allows the application of already consolidated optimization techniques for deductive databases. The mapping is rather straightforward and it is shown in Appendix 2.

As to the AL-BQM coupling, one of the main concerns is that the WAM, as top-down machine, consumes one tuple at a time, fetching new tuples on backtracking, while the BQM, as bottom-up machine, computes the whole answer at once. As we shall see, a simple mechanism will allow the BQM to save the computed answer and to return each tuple on WAM demand.

The remainder of this section gives more details about the BQM modules and the AL-BQM interaction.

4.1. The Static Compiler

The goal of the Static Compiler is threefold: i) for each literal symbol $o.p$, determine if the associated program $P_{o.p}$ is stratified, ii) for each stratified program, save the stratification along with enough information for a subsequent fast retrieval of the program itself, and iii) modify the AL metaschema by building up rules that allow the WAM to invoke the BQM only for stratified subprograms.

As a first task, the Static Compiler builds a compact symbolic representation of the whole KB based on the notion of dependency graph. Clearly, the analysis is restricted to the intentional part of the KB (a more precise distinction between classes and

instances in the framework of LOCO implementation is reported in Appendix 2).

In order to determine the sets of mutually recursive literal symbols (called clusters), the strongly connected components of the dependency graph are singled out, by using the Tarjan algorithm [Tar72]. Then, the condition of stratification of a program $P_{o,p}$ is checked, by verifying the absence of complementary literal symbols in each cluster of $P_{o,p}$. The relevant information concerning the recognized stratified programs are saved in the BQM metaschema. It is composed by two relations, namely *bqmPred* and *dependsOn*. The first relation describes all stratified literal symbols while the second one represents, in a compact way, the depends-on relation.

At this point the Static Compiler sets up the activation of the Run-Time Environment through the mechanism of AL external predicates. Such a mechanism represents the standard interface between the AL and external modules, allowing to associate a non-AL function to a predicate. In our case, the external unary predicate *bqm* constitutes the interface between the AL and the Run-Time Environment. In particular, for each o,p such that $P_{o,p}$ is stratified, the Compiler replaces the result of the AL compilation for p at the object o with the simple meta rule:

$$p(\bar{X}) :- bqm(p(\bar{X})).$$

As a consequence, the subsequent WAM code generation will produce a call to the main entry of the Run-Time Environment, whenever this is appropriate.

4.2. The Run-Time Environment

The BQM Run-Time Environment is activated by the WAM and is composed by two main blocks under the overall control of the *BQM manager* (see Figure 4.2): the *Dynamic Compiler*, that produces a (optimized) flat DATALOG program with negation for the query resolution; the *Executor*, a fix-point machine currently implemented on the WAM;

Figure 4.2: Architecture of the Run-Time Environment

The Run-Time Environment is invoked in three possible cases:

first call

a query on the literal symbol $o.p$ with binding pattern b is fired for the first time. In this case, the BQM manager activates the Dynamic Compiler for the dynamic compilation and optimization. Then, the Executor first produces WAM code for the implementation of the fix-point of the optimized program and the construction of the whole answer relation, and then invokes the WAM for the actual execution. Thereafter, a cursor on the answer relation is created and its first tuple is returned to the calling WAM environment. Additionally, the WAM code for the triple $\langle o.p, b \rangle$ is saved in the Query Archive.

backtracking

a query on $o.p$ is still active, but the set of tuples of the (already computed) answer have not been all consumed. This case occurs during the top-down WAM execution of a conjunction like $\dots o.1.p(X), X.q(Y) \dots$, where $o.1.p(X)$ has been solved by the BQM. In fact, each time that $X.q(Y)$ backtracks, a new tuple of the answer to the query $o.1.p(X)$ is required to the BQM. By means of a valid cursor associated to the query, the BQM is able either to return a new tuple from the answer relation, or to fail if no more tuples are available.

archived query

a query on $o.p$, with a given binding pattern, has been previously (dinamically) compiled, and then *archived*. Thus, the BQM manager immediately retrieves from the Query Archive (see Figure 4.2) the address of the corresponding WAM code, and requires its execution to the WAM with the actual query binding. As for a 'first call', the first tuple is returned. A typical situation is represented by a conjunction of the form $\dots o.1.p(X, Y), o.2.q(Y, Z) \dots$, where the subquery $o.2.q(Y, Z)$ is repeatedly passed (from the WAM) to the BQM, each time with a different binding for the variable Y . But, since the binding pattern is always the same, the WAM code for this query (with the given binding pattern) has been generated just the first time and then archived, so that no further dynamic compilation is required.

The next subsections contain a description of the two main blocks of the Run-Time Environment.

4.2.1. Dynamic Compiler

Given a query $o.p(\bar{X})$, where $\bar{X}$ is a list of (possibly bound) arguments, and o is an object, the main goal of the Dynamic Compiler is threefold: i)load the program $P_{o.p}$; ii)flat the program $P_{o.p}$ into a stratified DATALOG program with negation as failure; iii)optimize the resulting program for an efficient bottom-up execution.

The program loading is supported by the BQM Metaschema relations for identifying the necessary rules, and by the AL Metaschema for the actual rule retrieval.

Afterwards, the rules are converted into an internal BQM format, according to the technique presented in Appendix 2.

At this point, existing techniques for efficient bottom-up implementation of stratified DATALOG programs can be applied. To this aim, some rewriting

techniques, derived from deductive databases [SDMPDN87], based on the *magic* and the *counting* [BMSU86, BR87b, SZ87, SZ89] methods, are used. Such a rewriting produces two groups of rules: the first one exploits the binding propagation by computing sets (called *magic sets*) of facts that are relevant for the query evaluation; the second group contains the original rules opportunely modified so that their evaluation is restricted by such sets. Safety issues are also taken into account by a careful ordering of the goals in the rules. The same techniques have been successfully employed in the previous ESPRIT project KIWI [KIWI88], as well as in the LDL [NT88] and NAIL! [MUV86] systems.

4.3. Executor

The Executor is based on a bottom-up evaluation technique which results from the combination of the semi-naive method [BR87a] with the query/subquery approach [Vie86]. The advantage of the semi-naive method w.r.t. a pure (naive) bottom-up computation is that of cutting off a number of duplicated computations that are performed by the naive strategy, where the same tuples may be recomputed over and over. On the other hand, the query/subquery strategy improves on the straight bottom-up computation by allowing binding propagation.

As it has been already pointed out, the WAM is, for the current prototype, the 'final' target (or executor) of the BQM programs. Hence, the main task of the Executor is to enforce, on a top-down evaluator (i.e. the WAM), a bottom-up execution. The technique is well known and it is based on a careful use of some procedural features of Prolog, eg. rule ordering, cut and fail, asserting and retracting facts and suitable flags. A detailed description of such a technique can be found in [SDMPDN87].

Clearly, besides of the generation of the appropriate WAM code, the module is also in charge of the final activation of the WAM interpreter.

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Appendix 1: Stratified Programs with Extended Literals

Because of extended literals, the program P_o does not reduce to the rules coming from o and its super-objects, but has to include a number of rules coming from completely unrelated objects. In order to avoid the collection of totally useless rules, we try to foresee which objects of the KB can be involved in the computation.

To this aim, we first define the *range* of an extended literal symbol $X.q$ as the set of objects equals to: i) $\{o\}$, if X is equal to the object o ; ii) the set of all objects that own or inherit a rule for q , otherwise.

Let us consider, as an example, the following EOL program.

$$\begin{aligned}
 o' &= \{ p(X) :- q(Y), Y.r(X). \\
 &\quad \neg w(X) :- s(X). \\
 &\quad w(X) :- p(X). \} \\
 (o') \quad o &= \{ \neg p(X) :- s(X). \} \\
 (o) \quad o_1 &= \{ q(\bar{o}_1), s(a), s(b). \} \\
 \bar{o} &= \{ r(X) :- p(X). \} \\
 (\bar{o}) \quad \bar{o}_1 &= \{ p(a). \} \\
 \hat{o} &= \{ r(X) :- p(X). \}
 \end{aligned}$$

According to the above definition, the range of the extended literal $Y.r(X)$, appearing in the rule for p at o' , is equal to $\{\bar{o}, \hat{o}\}$ as they are the only objects with rules for r .

At this point, the program P_o associated to the object o can be identified as the set of rules that belong to: i) o and all its super-objects; ii) the programs $P_{o'}$ for each $o' \neq o$ in the range of each extended literal symbol $X.q$ appearing in P_o .

To remark the difference between literal symbols defined on different objects, a generic literal symbol p appearing in a rule of P_o will be denoted by a dot-notation like $t.p$ where $t=o$ if the rule is determined by condition i) above, or $t=o'$ when given by condition ii).

Let us consider again the objects defined in the previous example. In order to determine the program P_o , we first take all rules at o and o' . Thereafter, the same process is iterated for all objects in the range of $Y.r(X)$, yielding, after the inclusion of $P_{\bar{o}}$ and $P_{\hat{o}}$, the following program:

$$\begin{aligned}
 o.w(X) &:- o.p(X). & o.\neg w(X) &:- o.s(X). \\
 o.p(X) &:- o.q(Y), \bar{o}.r(X). & o.p(X) &:- o.q(Y), \hat{o}.r(X). & o.\neg p(X) &:- o.s(X). \\
 \bar{o}.r(X) &:- \bar{o}.p(X). & \hat{o}.r(X) &:- \hat{o}.p(X).
 \end{aligned}$$

Notice that the instantiation of the extended literal $Y.r(X)$ has generated two rules for $o.p$, one for each object in its range.

Now, it is not difficult to see that the dot-notation introduced above for denoting a generic literal symbol extends the validity of all definitions given for the stratification, to the presence of extended literals. Thus, the depends-on relation for the program P_o is represented by $(o.w, o.p)$, $(o.\neg w, o.s)$, $(o.w, o.\neg w)$, $(o.\neg w, o.w)$, $(o.p, o.q)$, $(o.p, \bar{o}.r)$, $(o.p, \hat{o}.r)$, $(o.p, o.\neg p)$, $(o.\neg p, o.s)$, $(\bar{o}.r, \bar{o}.p)$, $(\hat{o}.r, \hat{o}.p)$. Consequently, the dependency graph looks like in Figure Notice that the dependency graph for o includes the dependency graphs for $\bar{o}$ and $\hat{o}$.

Now, just as shown in Section 3, the programs needed to solve any query on o can be still singled out from the graph, and the stratification can be checked against the dependency graph by taking into account that two complementary literal symbols are of the form $o.p$ and $\neg o.p$. In the example, the programs $P_{o,w}$ and $P_{o,\neg w}$ are not stratified. In fact, the dependency graphs $DG_{o,w}$ and $DG_{o,\neg w}$, which coincide with DG_o , contain a cycle with $o.w$ and $o.\neg w$. On the other hand, the program $P_{o,p}$ is stratified, as it is clear from the dependency graph $DG_{o,p}$ shown in figure.

Appendix 2: From EOL to DATALOG

It has already been shown in [LMRR91,LR91] that a stratified OL program can be constructively transformed into an equivalent (stratified) DATALOG program. In this Appendix, we present, in a step-by-step fashion, the transformation as it has been devised for an actual implementation of EOL programs.

As a preliminary consideration, we note that, for efficiency reasons, it is convenient to introduce a distinction between the *class* and *instance* objects. An instance is an object that i) has only facts in its definition, ii) has no sub-object, and iii) has only one super-object, which is its *class*. All other objects are *classes*. Hence, programs associated to instances are only slightly different from those of their classes. Notice that such a distinction follows the dualism between schemes and instances of the traditional database approach, with the main advantage of limiting the analysis of the KB only to classes.

Now, let us assume that we have identified the (stratified) program $P_{o,p}$ needed to solve a query onto $o.p$, that the program has been divided into cluster of mutually recursive predicates, and that the associated stratification is known. Further, for simplicity, we suppose that each cluster is associated to a unique identifier c .

To begin with, all rules of $P_{o,p}$ are adorned such that each literal $\hat{o}.q(\bar{X})$ appearing in $P_{o,p}$ is rewritten as $q^c(\hat{o},\bar{X})$, where c is the identifier of the cluster $\hat{o}.q$ belongs to.

to and the object δ has become the first argument of the literal. However, in the following, we will omit the cluster identifier whenever no ambiguity arises. Further, notice that p and $\neg p$ are considered different positive literal symbols.

The first step is to generalize the rules so that the same program holds for a class and all its instances. Thus, a rule

$$q(\delta, \bar{X}) :- \text{body}(\delta, \bar{X}).$$

is rewritten as

$$q(S, \bar{X}) :- \text{body}(S, \bar{X}), \text{instance}(S, \delta).$$

where $\text{instance}(S, \delta)$ is a built-in predicate associating to the class δ the set S of its instances.

The second transformation aims to code into the clauses the overruling mechanism. Each rule of the form

$$q(S, \bar{X}) :- \text{body}(S, \bar{X}), \text{instance}(S, \delta).$$

such that $P_{o,p}$ contains a rule $\neg q(S, \bar{Y}) :- \dots, \text{instance}(S, \bar{o})$, where δ is a super-object of $\bar{o}$, and $\neg q$ denotes the complementary of q , is rewritten as

$$q(S, \bar{X}) :- \text{body}(S, \bar{X}), \text{instance}(S, \delta), \text{not}(\neg q(S, \bar{X})).$$

where *not* is interpreted as negation as failure.

The above rewritten rule simply states that a fact $q(t)$ can be derived only if the complementary fact $\neg q(t)$ cannot be derived. Notice that such a transformation fully captures the idea of overruling for stratified EOL programs.

An analogous approach is used for dealing with simple cases of non-stratified programs, where the non-stratification is induced by facts defined on the instances. The idea is that, whenever a rule $q(S, X) :- \text{body}(S, X), \text{instance}(S, o1)$ is contradicted by some facts for $\neg q$ declared at any instance of $o1$, then it is rewritten as

$$q(S, X) :- \text{body}(S, X), \text{instance}(S, o1), \text{not}(\neg q_{\text{base}}(S, X)).$$

where $\neg q_{\text{base}}$ will match only the facts for $\neg q$ defined on the instances.

A further transformation involves the management of extended literals. Given a rule $q^c(S, X) :- \dots, Y.t(Z), \dots$ let $o_1, \dots, o_i$ be the objects in $\text{range}(Y.t(Z))$ and let $c_1, \dots, c_i$ denote the clusters of respectively $o_1.t, \dots, o_i.t$. Then the rule is rewritten as:

$$\begin{aligned} q^c(S, X) &:- \dots, \bar{t}^k(Y, Z), \dots \\ \bar{t}^k(S, Z) &:- t^{c_1}(S, Z), \\ &\dots \dots \dots \\ \bar{t}^k(S, Z) &:- t^{c_i}(S, Z). \end{aligned}$$

where $\bar{t}$ is a new literal symbol, added for avoiding a duplication of the original rule (i.e. a rewriting for each t^{c_i}). Moreover, if any t^{c_i} is mutually recursive with q^c (i.e. any $c_i = c$), then $\bar{t}$ gets the cluster identifier c (i.e. $c = k$) and becomes mutually recursive with q^c , otherwise $\bar{t}$ gets a new cluster identifier.

The transformation of the stratified EOL program $P_{o,p}$ into an equivalent DATA-LOG program is now complete. It is also possible to see that the resulting program is stratified (in classical sense [ABW88]) and that its stratification can be derived from that of the original EOL program.

As a matter of fact, from one hand, the insertion of literals defined only by facts (e.g. *instance*) cannot affect the stratification S of the EOL program; on the other hand, the usage of $\text{not}(q)$ in the rules for $\neg q$ implies that such rules belong to a stratum higher than the stratum containing the rules for q : because of overruling, this fact is already granted in S . Finally, the addition of rules for the new literal symbol $\bar{t}^k$ modifies S in a very simple way: the rules for $\bar{t}^k$ are either in the same stratum S_q of the rules for q^c if $k=c$, or in a new stratum that must immediately precede S_q .