Accessing Relational and Higher Databases Through Database Set Predicates in Logic Programming Languages

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Hiermit erkläre ich, daß ich zur Abfassung der Dissertation keine anderen als die darin angegebenen Hilfsmittel herangezogen habe.

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Zusammenfassung

Die Koppelung logischer Programmiersprachen mit relationalen Datenbanksystemen erlaubt es, die Ausdrucksmächtigkeit logischer Sprachen mit der effizienten Speicherung und Verwaltung großer Datenbestände zu verbinden. Eine solche Koppelung ist für die Entwicklung sog. Datenbank-Expertensysteme von großem Interesse.

Auf der Ebene der Systemarchitektur sind die unterschiedlichen Evaluationsstrategien — Mengenevaluation in der Datenbank und Tupelevaluation in der logischen Programmiersprache — miteinander zu verbinden. Auf der sprachlichen Ebene ist die Datenbankabfragesprache so in die logische Programmiersprache einzubetten, daß der volle Umfang der vom Datenbanksystem zur Verfügung gestellten Abfragemöglichkeiten erhalten bleibt.

In bisherigen Ansätzen wurde versucht, entweder Datenbankkomponenten in die logische Programmiersprache oder aber eine logische Sprache in ein Datenbanksystem zu *integrieren*. In dieser Dissertation dagegen wird eine *Einbettung* des Datenbankzugriffs in eine logische Programmiersprache entwickelt.

Für diese Einbettung werden *Datenbankmengenprädikate* definiert. Datenbankmengenprädikate erweitern die aus logischen Programmiersprachen bekannten Mengenprädikate um Zugriff auf externe Datenbanken.

Datenbankmengenprädikate sind Prädikate der Form

```
db_set_predicate(ProjectionTerm,DatabaseGoal,ResultRelation)
```

`ProjectionTerm` und `DatabaseGoal` definieren den Zugriff auf die externe Datenbank in der Syntax der logischen Programmiersprache. `ResultRelation` enthält die Ergebnisrelation der Datenbankabfrage.

Der Datenbankzugriff erfolgt durch eine Übersetzung des Datenbankzieles in eine äquivalente Datenbankabfrage. Diese Abfrage wird an das Datenbanksystem übermittelt und dort ausgewertet. Die Ergebnisrelation wird an die logische Programmiersprache zurückgesandt und dort in einer Standard-Datenstruktur abgelegt.

Durch die Übersetzung des Datenbankzieles zur Laufzeit ist eine dynamische Formulierung des Datenbankzugriffs möglich, die es erlaubt, Abfragen weitestmöglich einzuschränken. Die Speicherung der Ergebnisrelation in einer Datenstruktur der logischen Programmiersprache erlaubt die Verwendung des vorhandenen Speicherverwaltungssystems der Programmiersprache. Beide Mechanismen tragen somit zu hoher Effizienz bei.

Als besondere Eigenschaft von Datenbankmengenprädikaten ist hervorzuheben, daß sie auch für den Zugriff auf höhere Datenbanken, z.B. solche mit strukturierten oder mengenwertigen Attributen (NF^2 Datenbanken), geeignet sind. Ein Zugriff auf derartige Datenbanken ist mit den bisher vorgeschlagenen Ansätzen nicht zu realisieren. In Datenbankmengenprädikaten dagegen sind die dazu notwendigen Operatoren implizit vorgegeben und müssen somit nicht eigens implementiert werden.

Datenbankmengenprädikate wurden im Rahmen einer praktischen Anwendung, der Syntheseplanung auf der Basis von Namensreaktionen in der organischen Chemie, entwickelt und werden in der Applikation **DedChem** eingesetzt.

Abstract

Coupled systems combine the high expressive power of logic programming languages with the efficient storage and administration of large amounts of data in database management systems. Coupled systems are a basic technology for the development of expert database systems.

For the implementation of coupled systems the following problems have to be solved: The different evaluation mechanisms implemented in the database management and the logic programming system respectively have to be coordinated on the system architecture level. On the system language level the database access has to be incorporated into the logic programming language in such a way that the full expressive power of the database query language is available.

Previous approaches to coupled systems have primarily tried to *integrate* a database system into the logic language system. In this thesis, I propose instead to *embed* database access into a logic programming language.

This embedding is achieved through *database set predicates*. Database set predicates extend the set predicates as they are known in current logic programming languages with access to external databases.

Database set predicates are predicates of the form

```
db_set_predicate(ProjectionTerm,DatabaseGoal,ResultRelation)
```

`ProjectionTerm` is a term, and `DatabaseGoal` is a – possibly complex – database goal formulated in the syntax of the logic programming language. `ProjectionTerm` and `DatabaseGoal` are translated to a database query. The query is evaluated in the database system, and the result is returned to the logic programming language where it is held in the standard datastructure `ResultRelation`.

Both `ProjectionTerm` and `DatabaseGoal` can be constructed at runtime. This allows a dynamic definition of database access to result in maximally restrictive queries which reduce the amount of data to be imported from the database system. The use of a standard datastructure allows the built-in memory management to be used, which also contributes to the overall efficiency of the approach.

An important feature of database set predicates, as compared to other approaches, is the high expressive power of its database access language. Access to higher database systems, e.g. databases with tuple-, list- or set-valued attributes, or even nested relations in NF^2 databases, and higher-order control, e.g. sorting or grouping is expressible. Other approaches to coupled systems do not support access to higher databases, and higher-order control has to be programmed explicitly.

Database set predicates will be implemented in the application program **DedChem**. **DedChem** is a coupled system for synthesis planning in organic chemistry based on name reactions.

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1

Introduction

The field of logic and databases aims at combining the sound theoretical foundation and the powerful and universal formalism of logic with the efficient and safe administration of large amounts of data of databases. Two major working areas have evolved, deductive databases [Gallaire/Minker 78, Gallaire et al. 84, Minker 88 b, Lloyd 87] and persistent logic programming languages [Appelrath 85, Jasper 90].

The field of logic and databases can be described on three levels: theory, concept and implementation.

1.1 Theoretical level

On the theoretical level the relationship between formal logic and logic programming on the one side and database models on the other side is analyzed.

A formal logic system consists of a logic language, a set of axioms formulated in the logic language, and a set of inference rules that allow the derivation of theorems from the axioms of the system.

Formal logic systems can be ordered hierarchically according to their expressive power. In propositional logic it is only possible to prove statements about complete sentences. First-order predicate logic introduces variables that stand for individuals. Universal or existential quantification of variables allows to express the relationships that hold between variables in a first-order sentence. Higher-order logic systems such as second order predicate logic, temporal logic [Kröger 87], or modal logic [Gabbay/Guenthner 84], extend predicate logic with quantification over predicates, the notion of time, and reasoning under uncertainty. However, for a large class of high-level applications the expressive power of first-order predicate logic is fully sufficient [Kowalski 79, Genesereth/Nilsson 87]. Often, all that is required is higher-order syntax to facilitate the formulation of special problems, but even in such cases the semantics of first-order predicate logic suffices [Chen et al. 90].

The major appeal of using first-order predicate logic as a programming language are its correctness and completeness properties. With these properties it is possible to *prove* correct a program written in a first-order predicate logic language.

Two developments opened the way for logic programming. The first was the proposal of the resolution rule by Robinson [Robinson 65], a sound and complete inference rule that made possible first-order predicate logic systems with only one inference rule and without non-logical axioms. The second development was the restriction of the logic language to Horn clauses. For Horn clause languages intuitive declarative and procedural semantics were proposed by Kowalski [Kowalski 79].

A logic program may be seen as a theory of first-order predicate logic. Its axioms, written as Horn clauses, capture the knowledge about the application either extensionally in facts, or intensionally through rules. The program is executed by providing a goal, i.e. a theorem that is to be proved through the application of the inference rules. If the proof succeeds, then the variable bindings computed during the evaluation are returned as a solution.

The classical relational database model can also be considered as a first-order predicate logic system [Gallaire/Minker 78, Kowalski 81, Parsaye 83, Gallaire et al. 84]. The axioms of this system consist of the database relation tables, and queries correspond to theorems. The evaluation of a query in the relational database model amounts to retrieving those columns and rows from the database relations that match the query conditions.

Despite their common foundations in first-order predicate logic there are two main differences between the relational database model and a logic programming language system, namely the different

- expressive power of the respective languages and the
- evaluation mechanisms employed in the respective system implementations.

Everything that can be expressed in the relational database model can also be expressed in a Horn clause language because each relational operator can be represented as a Horn clause. A formal system based on Horn clauses is thus said to be relationally complete. However, because recursion is expressible in Horn clause languages but not in the relational database model, the expressive power of Horn clause systems is greater than that of the relational database model.

In the relational database model an operation is defined over relations as a whole, and the result of an operation is again a relation [Codd 70]. Logic programming systems are theorem provers. In general they are based on resolution with the standard unification procedure in which each variable is bound to at most one atomic value. A proof returns the bindings of a single tuple. The evaluation in database systems is thus set-oriented, as compared to tuple-oriented in logic programming systems.

1.2 Conceptual level

In the context of logic and databases a coupled system is a system that couples a logic programming language with one or more database systems. The database systems provide persistent data storage and efficient access to large amounts of data, while the logic language provides the expressive power that is needed for the implementation of the application.

The conceptual level describes the pragmatics of coupling a logic programming language with external databases. It contains the requirements that an approach to coupled systems is designed to meet, and criteria to define the structure and quality of coupled systems. The general techniques employed in an approach are also described on this level.

There exist two main techniques to coupling a logic programming language with external databases: integration and embedding [Bever 86]. In an integrated coupled system, access to a database system is included in the programming language definition already. With embedding, access to databases is added to existing programming language through language or run time system modifications. Both techniques can be described in more detail by distinguishing a logical – or system language – and a physical – or system architecture – level [Bocca 86]. Together with the degree of coupling on both levels this results in structural criteria that may adequately describe the structure of coupled systems.

Qualitative criteria, such as expressive power, efficiency, implementation effort, or the independence of the external database system and the logic programming language, describe the properties of an approach to coupled systems and may be used to compare different approaches.

Dependencies exist between structural and qualitative criteria. The overall efficiency of a coupled system is determined by the degree of coupling on the physical level, and integration of the database language into the logic programming language.

Similar dependencies also hold among the qualitative criteria themselves. A trade-off exists between expressive power and efficiency because the evaluation of a high-level language is computationally more demanding than that of languages with restricted expressive power.

The architecture of a coupled system is determined by the application requirements the system is designed to meet. Constraints of such a kind are the types of external databases that are to be accessed, the access privileges to these databases, the availability of resources, and others. These constraints are not inherent to coupled systems, but they define the structure and thus to a large extent also the properties of a particular approach to coupled systems.

Because of the dependencies between external constraints, structural criteria, and the properties of a coupled system, any approach to coupled system is necessarily a compromise. This explains the variety of approaches, and it implies that any comparison of coupled systems must take into account the original system requirements.

1.3 Implementation level

On the implementation level the low-level implementation details of an approach to coupled systems are described. Such low-level details are the programming language used to implement a coupled system, the actual encoding of the interface mechanisms defined on the conceptual level, and information about the interaction of a coupled system with the underlying file system of an operating system environment.

1.4 Contributions of the thesis

The main contribution of the thesis is the proposal of a new approach to coupled systems, namely *database set predicates*. Database set predicates extend the definition of the set predicates [Warren 82] found in logic programming languages with access to arbitrary external relational or higher databases.

- The general idea of database set predicates is to *embed* — instead of integrate — database access into the logic programming language evaluation.

  The primary distinguishing feature of database set predicates is that database access is fully embedded into the logic language. In other approaches either the database is integrated into the logic language system, or there coexist distinct languages for the application program and the database access.

  A second distinguishing feature is that result relations as a whole are captured in a standard datastructure of the logic language. In other approaches, either the evaluation strategy of the logic language system is changed to match that of the database, or relations retrieved from the database system are either asserted into the logic language workspace — which effectively is a modification of the logic program — or their contents are returned to the logic programming language one record at a time — which causes considerable administration overhead and/or requires the use of a dedicated buffering mechanism to temporarily store the result relation.

  Finally, database set predicates may be used to simulate most of the other approaches to coupling databases to a logic programming language.

Furthermore, a graphical two-dimensional framework based on the structure of coupled systems and a set of qualitative criteria are proposed for the classification of coupled systems. The main properties of a coupled system can be derived automatically from the position that this system occupies in the matrix. This framework is used to describe the approaches to coupled systems which have been developed so far, and to motivate the current approach.

In the thesis an example from the world of flight connections and airplanes is used because it is highly intuitive. However, database set predicates were developed as part of a practical application.

This application is described in a chapter of its own because the application domain, organic chemistry, has so-far not been considered amenable to deductive database systems.

The specific task of the application is synthesis planning. Synthesis planning consists of finding a sequence of reactions so that a given substance can be produced. The requirements of the application exceed the expressive power of most current deductive database systems based on Datalog because it requires functions to build tree structures to adequately represent synthesis plans.

1.5 Position of the thesis on the three levels

The three levels theory, concept and implementation will now serve to position the thesis in the research field.

On the theoretical level database set predicates are higher-order language constructs because they refer to sets and functions. Function symbols are used as term constructors and are necessary for the datastructure that holds the result relation of the database query evaluation. However, the semantics of set predicates in general, and of database set predicates in particular, is within the semantics of first-order predicate logic [Warren 82, Chen et al. 90].

On the conceptual level database set predicates embed access to external databases. The same language is used to access external databases and to implement application programs, and standard datastructures are used to collect the result relations produced by the set-oriented database evaluation.

Database set predicates implement a physically loosely and logically tightly coupled system. The logic programming language and the relational database systems are separate systems connected through a communication channel. Database access requests are dynamically translated to database queries. These queries are transmitted to the database system and evaluated there. The result relation is returned as a whole back to logic programming language where it is placed in a list datastructure.

On the implementation level the actual implementation of database set predicates in Prolog and SQL is outlined.

1.6 Limitations of the thesis

Database set predicates have certain limitations which are briefly outlined here. A more detailed discussion and a description of how to overcome these limitations is given in the appropriate chapters.

These main limitations are

- high memory requirements,
- restriction of the database access language to the expressive power of relational database languages, and
- read-only access to the external database.

Of these, only the high memory demand is a limitation inherent to database set predicates. Both the language restriction and the read-only access are limitations of this thesis.

Storing entire result relations in a standard datastructure of the logic programming language potentially requires the allocation of large amounts of main memory in the logic programming language. Memory demand is reduced through small result relations. With database set predicates memory demand can be reduced through the formulation of maximally restrictive queries that yield minimal result relations. Furthermore, because a standard datastructure is used, the built-in memory management mechanisms, including garbage collection, can be used to deallocate memory as soon as the datastructure is no longer needed.

In this thesis, database set predicates are restricted to such database access requests that can be directly translated to a single relational query. However, access to more powerful databases is expressible by database set predicates, with the only limitation that the database access language be a first-order logic language (see [Lloyd 87, Ullman 88, Marti 89, Vieille/Lefêbvre 89] for a discussion and definition of *allowed* databases). In Chapter nine, access to NF^2 databases is discussed in detail.

In this thesis, database set predicates are restricted to read-only access to external databases. It is argued that for many applications, especially in the case of physically loosely coupled systems, updates are not necessary or even not allowed. However, it is possible to express updates through database set predicates either implicitly by calling them with the database goal expressing the update conditions and a fully instantiated third argument containing the update values, or explicitly through reserved database update commands. The use of database set predicates for updates is discussed in Chapter nine.

1.7 Structure of the thesis

The thesis is divided into three main parts, roughly corresponding to the description levels theory, concept and implementation.

Part one deals with the theoretical level. Chapter two is a brief introduction of the theory of first-order predicate logic and logic programming. In this chapter the relationship between the relational database model and Horn clause logic is described.

Part two corresponds to the conceptual level. Chapter three contains the terminology relevant to coupled systems. Chapter four contains the graphical framework and presents the structural and qualitative criteria for coupled systems. Chapter five gives an overview and a discussion of existing

coupled systems. From this discussion database set predicates are motivated. In chapter six, set predicates as they are known in logic programming languages, and their extension to database set predicates, are presented. In this chapter the specific properties of database set predicates are discussed in detail.

In part three the implementation level is dealt with. Chapter seven describes the translation of Prolog database goals to SQL and discusses the communication channel. Chapter eight contains a sample application from organic chemistry. Extending database set predicates to access higher databases and the incorporation of database updates is discussed in Chapter nine. In Chapter ten, a conclusion summarizes the work presented.

Part I

Theory

2

Logic programming and the relational database model

The common foundations for the relational database model and logic programming lie in first-order predicate logic. Relational calculus, a sublanguage of first-order predicate logic languages, has been proven to be equivalent in expressive power to relational algebra [Aho/Ullman 79, Maier 83]. Horn clause languages, a syntactically restricted representation of first-order formulas, have been given a declarative and a procedural semantics [Kowalski 79], and this has led to the implementation of logic programming languages. Thus, with a restriction of the logic programming language to a language equivalent in expressive power to the relational calculus, relational databases can be accessed from programs written in a logic programming language.

2.1 Relational database model

A *domain* is a set of meaningful values. A relation R is a subset of the cartesian product of domains D_i:

$$R \subseteq D_1 \times ... \times D_n$$

A *relation* can be represented as a relation table. A *tuple* or *record* corresponds to a row in this table, an *attribute* to a column. A tuple is written as $(a_1,...,a_n)$, with a_i values from the appropriate attribute domains.

An attribute is referred to by an attribute name that is unique for a given relation. This attribute name can be made globally unique by making it a *qualified attribute name* through using the relation name as a prefix.

Two important properties of relations are:

- A relation does not contain duplicate tuples.
- The tuples in relations are not ordered.

The first property means that no two tuples in a relation are the same. The second property means that any representation of a relation displays just one possible ordering of tuples — any other ordering is just as valid.

A relation is in *first normal form* (1. NF) if its attributes are atomic values.

2.1.1 Relational algebra

The relational algebra consists of the standard set operations

- union,
- intersection,
- difference

In relational algebra, these set operations are restricted to union-compatible relations. Two relations `R` and `S` are *union-compatible* if they both have the same number of attributes, and the *i*-th attribute of either relation must be based on the same domain D_i (the attributes must not necessarily have the same attribute name in both relations).

The following operations are defined specifically for the relational database model:

- The *selection* operation selects from a relation `R` all those tuples that match a given selection condition.
  Selection is written as $\sigma_{cond}(R)$, where `cond` is the selection condition.
- The *projection* of the relation `R` on attributes $A_1,...,A_n$ is the set of all tuples that contain only the values of the attributes specified by the projection operator.
  Projection is written as $\pi_{attlist}(R)$, where `attlist` is a list of attributes to project on.
- A *join* concatenates the tuples of two relations `R` and `S` for all those tuples for which a join condition holds between pairs of attributes from both `R` and `S`.
  A join is written as $R[att_r \ \theta \ att_s]S$, where θ expresses the condition that holds between attributes of `R` and attributes of `S`.
  A special case is the *natural join*, where the condition that must hold is the equality of the attribute values of both relations. Only one of the attributes of the equality comparison is retained in the resulting relation.

Relational algebra is a *closed system*: each operation is defined over relations, and the result of an operation is again a relation. Because of this *closure* property, the operations of the relational algebra can be nested to result in complex relational expressions.

Example

`Flight` and `Plane` are two relation tables defined as

```
Flight := (flightno × departure × destination × plane)
Plane := (type × seats)
```

The domain of `flightno` is the set of flight numbers, the common domain of `departure` and

`destination` is the set of airports, that of `plane` and `type` is the set of types of airplanes, and that of `seats` the natural numbers from 0 to 1000.

$\pi_{\texttt{departure,destination,plane}}$(`Flight [Flight.plane = Plane.type] Plane`)

expresses a projection on the attributes `departure`, `destination`, and `plane` on the result relation of a natural join over the relations `Flight` and `Plane`.

Note that implicitly the attribute name `plane` from the relation `Flight`, which is on the left side of the join condition, is taken as the attribute name of the corresponding result relation.

♦

In any complex relational expression the projection operations inside a relational expression can be replaced by one single projection operation applied to the result of the evaluation of the expression without projection. The intermediate relations generated through a complex relational expression without projection may be larger than those generated with projection, but the final result is identical. The converse, however, is not true: in general it is not possible to push projections into a complex expression because this might delete attributes which are needed in later operations.

An algebra consisting of the operations union, intersect, difference, selection, projection, and join is said to be *relationally complete*. Further operations have been devised. However, they can all be represented by the operations defined above. Relational completeness is considered a yardstick for the expressive power of a relational database language [Maier 83, Maier/Warren 89, Abiteboul et al. 90].

Extensions of the relational database model

In the relational database model arithmetic functions over sets of attribute values cannot be expressed. However, for practical applications, e.g. report writing, and statistical analyses of the data stored in the relation tables, such functions are desirable. Klug [Klug 82] defined *aggregate functions* as extensions to the relational algebra and the relational calculus and showed that the expressive power of both formalisms is equivalent.

In his definition, the aggregate formation operator is written as

`RelExpr<Attributes,Function>`

with `RelExpr` a relational expression, `Attributes` a subset of the set of attributes occurring in `RelExpr`, and `Function` the name of the aggregate function, qualified by the attribute to which it is to be applied.

The aggregate formation operator partitions the result relation of the relational expression `RelExpr` into partitions with equal values for the attributes in `Attributes`, applies the function `Function` to the appropriate attribute in each partition, and outputs the value of the attributes according to which the partitions were made together with the function value for each partition.

Example

The relation `Flight` contains the following entries:

flightno	departure	destination	plane
sw1	zurich	geneva	b-737
sw2	geneva	paris	a-320
sw2	zurich	paris	b-737

The aggregate function `count` counts the number of entries in a relation.

`Flight<departure,count`$_{\texttt{destination}}$`>`

partitions the relation into two equivalence classes according to the value of the attribute `departure`, i.e. `zurich` and `geneva`. The function `count` is computed for each partition, and the result is the relation

departure	count$_{\texttt{destination}}$
zurich	2
geneva	1

♦

2.1.2 SQL

SQL is the current database language standard for relational databases [Date 89]. SQL consists of a data definition language and a data manipulation language. The data manipulation part of SQL consists of a query and update language and a transaction language.

SQL is a typed language. The basic types are `CHARACTER`, `NUMERIC`, `DECIMAL`, `INTEGER`, `SMALLINT`, `FLOAT`, `DOUBLE PRECISION`, and `REAL`, some of which may carry additional precision or length information.

A simple SQL query consists of at least a `SELECT` and a `FROM` part, and, optionally, a `WHERE` part.

`SELECT <columnlist>` defines the columns of the result relation for the query. Columns may be either constant or function values, or attributes. Note that duplicates are retained implicitly, contrary to the definition of a relation in the relational database model. The keyword `DISTINCT` eliminates duplicates from the result relation.

`FROM <tablelist>` lists the relation tables from which data is to be retrieved. In the `FROM` part, relation tables may be qualified by range-variables which uniquely identify each relation table.

Example

"Retrieve all departures and destinations from the relation table `Flight`" is expressed in SQL as

```
SELECT DEPARTURE,DESTINATION
FROM FLIGHT
```

This query results in a relation with two columns named departure and destination. With `DISTINCT` included in the `SELECT` part, the number of rows may be lower than in the original

relation due to the elimination of duplicate entries.

♦

`WHERE <conditionlist>` contains conditions for the restriction of the query. Such conditions are either selection or join conditions, and they are connected via `AND` or `OR`.

Example

"Retrieve all destinations which can be reached from Zurich" is expressed in SQL as

```
SELECT DEPARTURE, DESTINATION
FROM FLIGHT
WHERE DEPARTURE = "zurich"
```

The following query requires a join over the relations `Flight` and `Plane`: "Retrieve all destinations which can be reached from Zurich with a big plane, i.e. a plane with more than 150 seats"

```
SELECT DEPARTURE, DESTINATION
FROM FLIGHT F, PLANE P
WHERE F.DEPARTURE = "zurich" AND F.PLANE = P.TYPE AND P.SEATS > 150
```

Note that the range variables `F` and `P` have been introduced here to uniquely identify the relations `Flight` and `Plane` respectively, and that the attributes in the `WHERE` part are qualified through the range variable to make attribute names unique.

♦

The infix operator `UNION` takes two queries as arguments and computes the union of two relations. Nested queries are allowed in the `WHERE` part.

Example

"Retrieve all planes which are not currently used on any flight" is expressed as

```
SELECT P.TYPE
FROM PLANE P, FLIGHT F
WHERE NOT EXISTS
(SELECT F.PLANE
 FROM FLIGHT
 WHERE P.TYPE = F.PLANE)
```

♦

SQL includes extensions to the relational algebra such as aggregate functions, grouping and sorting. These extensions augment the expressive power of SQL and make it suitable for real-world applications.

Aggregate functions compute values over sets of attribute values. For this, the relation may be partitioned using `GROUP BY`. `GROUP BY <attributelist>` is used to partition the relation according to the values of the attributes in `<attributelist>`. `HAVING <conditionlist>` is the equivalent of `WHERE` for groups, i.e. it is used to express selections on the values of grouping attributes.

The SQL aggregate functions are `min`, `max`, `avg`, `sum`, and `count`. An aggregate function may occur as the sole entry in the `SELECT` part, or together with other aggregate functions only.

`ORDER BY <columnlist>` sorts the result relation according to the values of the columns specified in the list.

2.2 First-order predicate logic

The alphabet of a first-order logic language consists of (the definitions closely follow [Lloyd 87])

- constants (denoted as strings beginning with lower case letters),
- variables (denoted as strings beginning with upper case letters or an underscore)
- n-ary function and predicate symbols,
- the connectives $\wedge$, $\vee$, $\neg$, $\rightarrow$, $\leftrightarrow$,
- the universal quantifier $\forall$ and the existential quantifier $\exists$, and of
- punctuation symbols.

A *term* is either a

- constant, a
- variable, or
- $f(t_1,...,t_n)$ where f is an n-ary *function symbol* and the t_i, $i=1..n$ are terms.

A *formula* is defined inductively as

- if p is an n-ary *predicate symbol* and the t_i, $i=1..n$ are terms, then $p(t_1,...,t_n)$ is a formula, also called an *atomic formula* or *atom*.
- if F and G are formulas, then so are $\neg F$, $F \wedge G$, $F \vee G$, $F \rightarrow G$, and $F \leftrightarrow G$
- if F is a formula and X a variable, then so are $\forall X\ F(X)$ and $\exists X\ F(X)$.

A *positive literal* is an atom, a *negative literal* is an atom preceded by the unary connective $\neg$.

A *clause* is a sequence of literals connected through $\vee$. As a convention, a sequence of literals

$$A_1 \vee ... \vee A_n \vee B_1 \vee ... \vee B_m$$

with A_i positive and B_j negative literals is written as

$$A_1, .., A_n \leftarrow B_1, ..., B_m$$

Note that the "," on the left side the implication stands for $\vee$, while on the right side of the implication it stands for $\wedge$.

A *Horn clause* is a clause with at most one positive literal on the left side of the implication arrow.

The literal on the left side of the implication is called the *head*, the literals on the right side are called the *body* of the clause.

A *program clause* is either a

- *unit clause*, a clause with an empty body: $p \leftarrow$. (also written as p.)
- *rule*, a clause of the form: $p \leftarrow q_m, \ldots, q_n$.
- *goal*, a clause with an empty head: $\leftarrow q_m, \ldots, q_n$.

A clause is *ground* if it does not contain variables. A *fact* is ground unit clause. A goal is a *simple goal* if it contains only one literal, a *complex goal* otherwise.

All variables in a program clause are assumed to be universally quantified. This assumption is permitted because the existential quantifier for a variable X can be replaced by a Skolem function which takes as arguments the universally quantified variables that determine the value of X. Under this assumption, the universal quantifiers can be omitted.

A rule is *range-restricted* if all the variables in its head also occur positively in its body. In the rest of the thesis only range-restricted rules will be considered.

A *predicate* is a set of clauses with common predicate symbol and arity. The *extension* of a predicate is the set of facts with the same predicate symbol and arity, whereas the *intension* is given through its rules. A predicate is defined *extensionally* if its definition consists of facts only, and *intensionally* otherwise.

A rule $p \leftarrow q_1, \ldots, q_n$ is *recursive* if it contains in its body a literal q_i with the same predicate symbol and arity as p.

A predicate p is *recursive* if it contains a recursive rule. Two predicates p and q are *mutually recursive* if p contains q in the body of a rule ("p *calls* q"), and q contains p in the body of a rule.

Example

```
connection(From,To) ← flight(No,From,To,Plane).

connection(From,To)←
  connection(From,Transit),
  flight(No,Transit,To,Plane)
```

defines the predicate connection/2. The predicate is recursive.

♦

A *logic program*, *program* for short, consists of a finite set of program clauses.

2.2.1 Evaluation of logic programs

A logic program may be used to infer the truth or falsity of a theorem with respect to the logic program. An evaluation thus consists of finding a proof for the theorem from the clauses of the logic program.

Substitution and Unification

During the construction of a proof *variable bindings* are computed in which a variable `v` is bound to a term `t`. Such a variable binding is written as `v/t`. A *substitution* is a set of variable bindings v_i/t_i, where the distinct variables v_i of a term are bound to a term t_i with $v_i \neq t_i$ and $v_j \neq v_i$ for $i \neq j$.

The application of a substitution to a clause yields an *instance* of a clause.

Example

The application of the substitution `{X/geneva}` to `flight(sw1,zurich,X,b-737)` is written as

```
flight(sw1,zurich,X,b-737) {X/geneva}
```

and yields the ground instance

```
flight(sw1,zurich,geneva,b-737).
```

♦

Unification is the process of making two formulas syntactically identical through a substitution. If there exists such a substitution or *unifier*, then there also exists a unique *most general unifier (mgu*). A unifier θ for a set of formulas F is an *mgu* for F if there exists for any other unifier σ of F a substitution γ such that $\sigma = \theta\gamma$.

Example

The *mgu* of the following two clauses

`flight(sw1,zurich,X,b-737)` and
`flight(Y,zurich,Z,b-737)`

is `{Y/sw1,X/Z}`.

♦

An evaluation can be either *top-down*, starting with the original goal and using resolution, *bottom-up*, starting with the program clauses in a fixed-point computation, or a combination of both.

In a top-down evaluation the starting point of the evaluation is the goal to be proved. In each evaluation step the goal is replaced through the subgoals of a clause that can be unified with the goal. This evaluation strategy is also called *backward chaining* because the direction of evaluation goes from rule head to the body in the opposite direction of the "←" implication.

In a bottom-up evaluation the starting point of the evaluation is the set of facts. In each evaluation step a the set of facts is augmented with the heads of rules whose bodies evaluate to true. The evaluation ends if the original goal is included in the set of derived facts. The direction of evaluation follows the "←" implication, and it is thus also called *forward chaining*.

Top-down evaluation with SLD resolution

Top-down evaluation relies on the resolution rule [Robinson 65], a sound and complete inference rule, to derive new clauses from the clauses stored in the program. This derivation is commonly done through a refutation theorem prover. A refutation proof adds the negation of the clauses that are to be proved to the set of program clauses and tries to derive a contradiction. If such a contradiction can be found, then the negation of the clauses to be proved is false, hence the clauses are true.

SLD resolution is a refutation proof procedure for logic programs. The general procedure of SLD resolution is as follows:

- The original goal is taken as the first resolvent.
- In a derivation step, a clause from the resolvent is selected through a selection function. For this selected clause a program clause is chosen and the most general unifier of the two clauses is computed. In the current resolvent, the selected clause is replaced by the body of the program clause and the most general unifier is applied to the current resolvent.
- Derivation continues until the empty resolvent is reached which is the case when a proof has been constructed.

The resolvent may actually become smaller in each derivation step. If a rule has been chosen from the program clauses, the new resolvent will contain at least as many goals as the previous resolvent. However, if a fact is chosen, the new resolvent contains less goals than the previous one because the selected goal is deleted from the resolvent, and there is no clause body to add.

In each derivation step variable bindings are computed. Any variable in a goal may thus receive a binding during the proof. In fact, except for programs where the existence of a proof suffices, the variable bindings are the results one really is interested in.

A *solution* is the set of bindings for the goal variables computed during the proof of a goal. An *instantiation* is the application of a solution to a term.

Note that there may exist more than one proof for a given goal, each resulting in a solution. The set of all solutions to a goal is called the *solution set*.

SLD tree

An SLD resolution can be represented as an SLD tree. The root of the SLD tree contains the original goal. A node represents a resolvent and an edge corresponds to one derivation step in the resolution. In each derivation step exactly one clause from possibly many clauses whose heads can be unified with the selected goal is chosen through a search rule.

Each node in the SLD tree is labelled with the current resolvent. The selected goal for the next derivation step is underlined. A goal for which there is no unifiable clause is called a *failure node*, a branch in the SLD tree with a failure node as its leaf is a *failure branch*. A branch with the empty

resolvent as its leaf is a *success branch*. Each edge in the SLD tree is labelled with the most general unifier *mgu* of the derivation step.

The variable substitutions for each success branch define exactly one solution of the goal at the root of the success branch.

Example

The resolution of the goal ← `capacity(zurich,Destination,Seats)` with the program given below

```
capacity(Departure, Destination, Seats) ←
  flight(Departure, Destination, Type),
  plane(Type, Seats).

flight(zurich,geneva,b-737).
flight(zurich,paris,a-320).
flight(zurich,london,b-737).

plane(b-737,150).
```

can be represented as the SLD tree in Fig. 1.:

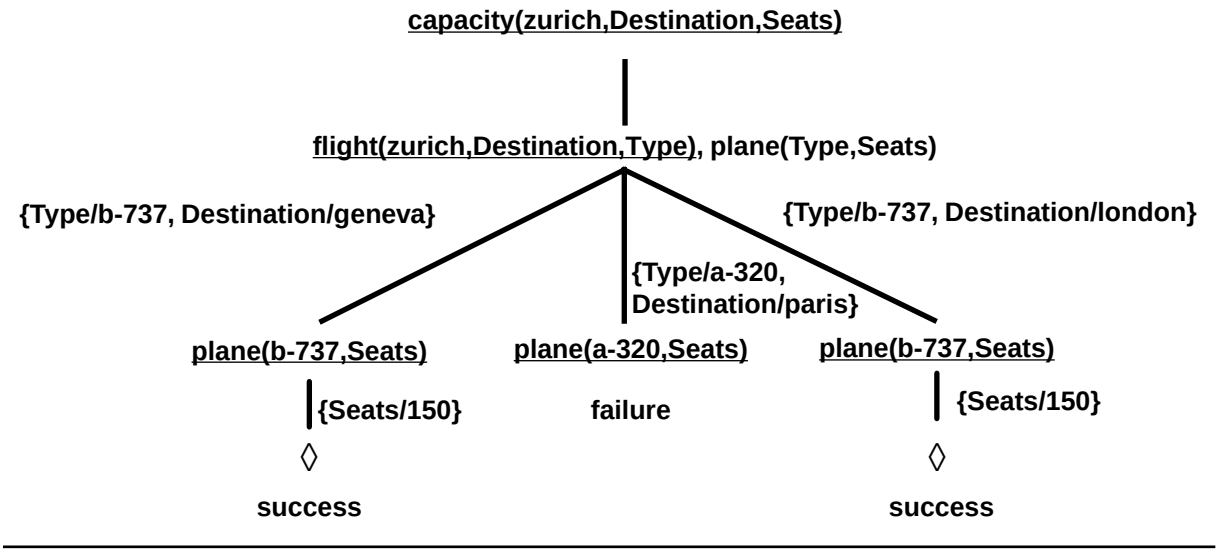


Fig. 1. SLD - tree of sample goal

The two solutions to the top-level goal

← `capacity(zurich,Destination,Seats)`

are

`{Destination/geneva,Seats/150}` and

`{Destination/london,Seats/150}.`

The application of the solutions to the goal term results in the two terms

`capacity(zurich,geneva,150) and capacity(zurich,london,150).`

The subgoal ← `plane(a-320,Seats)` cannot be proved from the database and hence there

is no solution for `capacity(zurich,paris,...)`.

♦

2.2.2 Abstract interpreter

The proof procedure informally described above is now presented as an abstract interpreter for logic programs (the empty resolvent is denoted by the symbol ◊. A fact is a clause with an empty body, written as `ClauseHead` ← ◊).

```
prove(◊).

prove(CurrentResolvent)←
  select_goal(CurrentResolvent,Goal),
  select_clause(Goal,(ClauseHead ← ClauseBody),Unifier),
  replace_goal(Goal,CurrentResolvent,ClauseBody,ReducedResolvent),
  apply(Unifier,ReducedResolvent,NewResolvent),
  prove(NewResolvent).
```

In this interpreter, variable substitutions are not represented explicitly. Only the most general unifier is shown to make its application to the whole resolvent visible.

Example

The logic program consists of the following clauses:

```
flight(sw1,zurich,geneva,b-737).
flight(sw2,zurich,paris,a-320).
flight(sw5,paris,london,b-737).

connection(From,To)←
  flight(_,From,To,_).

connection(From,To)←
  flight(_,From,Transit,_),
  connection(Transit,To).
```

The goal to be proved is ← `connection(zurich,X)`.

This goal is supplied to the abstract interpreter `prove` as the first resolvent which then becomes `prove(connection(zurich,X))`.

`select_goal(connection(zurich,X),Goal)` is called. There is only one goal in the resolvent and hence it must be selected. `Goal` thus becomes `connection(zurich,X)`. `select_clause` tries to find a matching clause for the current goal and computes the most general unifier.

In this case, assume that the first connection clause has been chosen. The most general unifier of `connection(zurich,X)` and `connection(From,To)` is `{From/zurich,To/X}`.

`connection(zurich,X)` is now deleted from the resolvent, and the body of the program clause is added to the resolvent which now becomes `flight(_,From,To,_)`. The unifier is applied to the resolvent to result in `flight(_,zurich,X,_)` as the new resolvent.

The derivation continues with the new resolvent through a recursive call to `prove(flight(_,zurich, X,_))`. The matching clauses for the resolvent are the first two program clauses.

Assume that the second clause is chosen. The unifier of the resolvent `flight(_,zurich, X,_)` and `flight(sw2,zurich,paris,a-320)` is `{X/paris}`. The use of the anonymous variable _ indicates that its binding is of no interest and thus it is neglected. However, the binding of `X` is returned.

The resolvent now becomes the empty resolvent ◊ because `flight(sw2,zurich,paris,a-320)` is a fact. The call to `prove` with the empty resolvent terminates the proof procedure.

As a result, the variable bindings for the variables of the original goal are returned. The solution to the goal ← `connection(zurich, X)` is `{X/paris}`.

♦

This abstract interpreter does not specify

- *which goal* to select from the current resolvent, nor
- *where* to place the body of the unified clause in the resolvent.

In the above example program clauses were chosen arbitrarily. The problem of selecting a goal from the resolvent did not arise because at any time there was at most one goal in the resolvent. In an actual implementation of a logic programming language the selection of a goal from the current resolvent is defined through a *computation rule* or *selection function* in the abstract interpreter. The replacement of a goal in the resolvent through its body is defined through the *search rule*.

In terms of a proof tree, the computation rule determines how to construct the tree, whereas the search rule determines how to traverse the tree in the course of a proof. In SLD resolution, the search rule always selects the first subgoal in the resolvent, and the computation rule always places the body of the selected clause before any other goal in the resolvent which results in a depth-first construction of the SLD tree.

Note that success or failure to prove a goal in a finite number of steps is independent of the computation rule, but requires a fair search rule, i.e. a search rule which guarantees that all clauses are tried [Lloyd 87].

Negation as failure

SLD resolution can be enhanced through a restricted form of negation to result in SLDNF resolution. *Negation as failure*, denoted by the symbol `not`, is a weaker form of negation than full negation of first-order predicate logic, or even negation under the closed world assumption [Reiter 78]. `not G` expresses only "`G` cannot be proved" rather than "`G` is not true" [Clark 78].

Negation as failure is *safe*, i.e. it yields the same result as negation under the closed world assumption, only for goals whose arguments are all bound. With unbound variables in the negated goal negation as failure does not yield the expected result but instead the computation *flounders*.

Example

The following clauses are given:

```
railroad_station(zurich).
railroad_station(berne).

airport(zurich).
```

Suppose one wants to find those cities that do not have an airport, but are railroad stations.

```
← not airport(City), railroad_station(City).
```

The expected answer is `City = berne`, but instead the goal fails. The reason for this is that `not airport(City)` calls `airport(City)`, which succeeds with `City` being bound to a value. `not` turns the success into a failure and undoes any variable binding, and thus the whole query fails.

Reordering the subgoals in such a way that the variables occurring in the negated subgoal are bound by positive subgoals gives the expected result:

```
← railroad_station(City), not airport(City).

City = berne
```

♦

For a detailed discussion of negation and negation as failure see the book by Lloyd [Lloyd 87], or the article by Shepherdson [Shepherdson 88].

2.2.3 Prolog

Prolog is a programming language based on Horn clause logic. Its development was motivated by Kowalski´s research result that Horn clauses have a declarative as well as a procedural reading [Kowalski 79].

A Horn clause

$A \leftarrow B_m, \ldots, B_n, 0 \leq m \leq n$

can either be read declaratively as

> A is valid if $B_m \wedge \ldots \wedge B_n$ is valid.

or procedurally as

> To achieve A, do B_m, …, do B_n.

The *procedural* (or *operational*) semantics of Horn clauses is the basis of all implementations of logic programming languages. Note that this procedural semantics does not prescribe a particular order in which the subgoals in the body of the clause are to be evaluated.

Prolog was defined by Colmerauer and Roussel [Roussel 75] at the University of Marseille and a first interpreter was implemented there. A Prolog compiler was first implemented by Warren and Pereira in Edinburgh [Warren 83].

The following syntax definition of Prolog follows the de-facto standard “Edinburgh” syntax as defined in [Clocksin/Mellish 87].

- A *constant* is either an atom, or a number. An atom is written as a sequence of characters, beginning with a lower case letter, and delimited by a space or a punctuation mark. Alternatively, if the atom is to begin with a capital letter, or contain punctuation marks or spaces, it can be enclosed in single quotes. Numbers are denoted by a sequence of digits including sign, decimal point or exponent symbol.
- A *variable* is denoted as a sequence of characters beginning with capital letters or an underscore.
- A *structure* (also called *compound term*) consists of a functor and a set of arguments enclosed in parentheses. Each functor is assigned an arity, and a functor is uniquely identified by the pair functor/arity. A functor is an atom, and the arguments are terms.

A special structure is the list. The empty list is written as `[]`, and `[Head|Tail]` denotes a list with the first element the variable `Head`. The vertical bar separates the elements on the left of the bar from the rest of the list, which is a list itself, represented by the variable `Tail`.

Example

`john mary ‘Loves’ 1234` are constants,
`Head Tail _X` are variables,
`loves(john,X)` is a compound term with the first argument a constant, the second argument a variable,
`[john,loves,mary]` is a list with three constant elements.

♦

Program clauses are also terms. Facts are simple compound terms, rules are terms with the binary functor “`:-`”, and goals are denoted by the unary functor “`?-`”.

Operators are functors with a predefined meaning (which can be redefined). The set of Prolog operators includes

- =/2, which succeeds if its two arguments can be unified,
- comparison operators, e.g. >/2, =</2, @</2,…, which succeed if the specified comparison holds between the two arguments. Note that for comparison operations all arguments must be bound.
- `is`/2, which succeeds if the argument on the left side can be unified with the result of the evaluation of the arithmetic expression on the right side,
- arithmetic operators, e.g. +/2, -/2, */2, //2.

The inference engine of Prolog is a concretization of the abstract interpreter presented in section 2.2.2. Prolog implements SLDNF resolution with a left-to-right computation rule, and a depth-first search rule. This means that the computation rule selects the leftmost subgoal from the current resolvent and that the search rule replaces this subgoal with the body of the program clause it was unified with successfully.

The depth-first computation rule together with the search rule can be implemented with a stack datastructure which holds the current resolvent. This implementation is space efficient because the maximum length of the stack is equal to the depth of the SLD tree of the original goal. The top element of the stack corresponds to the left-most subgoal in the resolvent. Replacing the left-most goal from the resolvent by the body of the unifying clause amounts to popping the top element off the stack, and pushing the body of the unifying clause into the stack.

Note that this search rule may lead to non-terminating evaluations with mutually or left recursive predicates. The search rule is only *correct*, but not *complete*. There may exist a proof for a given goal, but due to its fixed search rule Prolog fails to find this proof.

Example

The following program succeeds if there exists a connection between `Departure` and `Destination` via `Route`.

```
flight(sw1,zurich,geneva,b-737).
flight(sw2,geneva,paris,a-320).
flight(sw3,paris,london,b-737).
flight(sw4,zurich,london,b-747).

connection(Departure,Destination,Route):-
  connect(Departure,Destination,[],Route).

connect(Departure,Destination,SoFar,[Destination,Departure|SoFar]):-
  flight(_,Departure,Destination,_).

connect(Departure,Destination,SoFar,Route):-
  flight(_,Departure,Transit,_),
  not member(Transit,SoFar),
  connect(Transit,Destination,[Departure|SoFar],Route).
```

The program is started through the goal

```
?- connection(zurich,london,Route).

Route = [london,paris,geneva,zurich];
Route = [london,zurich]
```

Further solutions can be computed by forcing Prolog to backtrack. Entering a semicolon ; will force the current evaluation to fail and start the search for another solution. If there exist further solutions, they will be displayed, otherwise the evaluation fails with a system dependent message, e.g.

```
no more solutions.
```

The program can also be run “backwards”, e.g. by supplying only the route. The goal

```
?- connection(Departure,Destination,[london,paris,geneva,zurich]).
```

succeeds with

```
Departure = zurich
Destination = london;

no more solutions.
```

In fact, the program runs safely with any instantiation pattern (also called *mode*) of its arguments.

♦

Prolog features non-logical extensions which make it a general purpose programming language, but which do not have a declarative semantics.

- Extra-logical predicates achieve side effects during their evaluation. Typical examples are I/O predicates such as `read`/1 or `write`/1, dynamic database update predicates such as `assert`/1 or `retract`/1, or predicates that retrieve clauses from the program code, e.g. `clause`/2.
- Meta-level predicates query the state of a proof, treat variables as objects of the language, and allow the conversion of datastructures to goals [Sterling/Shapiro 86]. `var`/1 and `nonvar`/1 succeed if their argument is a variable respectively not a variable. Comparison of nonground terms is expressible by ==/2, which succeeds if its arguments are *identical* (which is stronger than *unifiable*: `?- 5=X` will succeed and unify `X` with `5`, but `?- 5==X` will fail). The predicate `call`/1 converts its argument into a goal, and succeeds if the evaluation of this goal succeeds.
- Control predicates affect the procedural behavior of a program. The cut, written as `!`/1, commits the evaluation to the current clause. Alternatives for the current clause, and alternatives for the goals before the `!`/1 in a clause are not tried. The cut thus amounts to pruning subtrees in the SLD tree.
  The if-then-else construct of procedural language is defined through the cut. It is written as ->/2, and can be defined as

```
->(P,(Q;_)) :- call(P),!,call(Q).
->(_,(_;R)) :- call(R).
```

Prolog is the most widespread logic programming language today. Various implementations, many of which have extensions to allow co-routining, delayed evaluation, safe negation, higher-order constructs etc. are commercially available, or in the public domain. The international standards committee is currently establishing a Prolog standard [Scowen 90].

2.3 Relationship between logic and the relational database model

First-order predicate logic languages feature negation, recursion, and function symbols. Through successive *restrictions* the expressive power of logic languages can be reduced. A first restriction, namely the elimination of function symbols, results in the language known as Datalog [Ullman 88,

Gardarin/Valduriez 88]. In a second restriction only non-recursive clauses are allowed. With this restriction the expressive power of the language is equivalent to that of relational calculus, and hence, with relational algebra [Aho/Ullman 79, Parsaye 83, Maier 83].

Note that negation is needed to express in relational calculus the difference operation of relational algebra. In the context of databases the closed world assumption is very natural, and therefore full negation of first-order predicate logic is not required.

2.3.1 Logic languages and relational database model

Any relational algebra operation may be expressed in a relational calculus formula, and any formula of the relational calculus can be represented through Horn clauses. Thus it is possible to express any relational algebra operation in a logic programming language based on Horn clauses. However, the converse is not true because the expressive power of an unrestricted logic programming language is greater than that of relational calculus or algebra.

With a suitable restriction the expressive power of the logic programming language can be made equal to the expressive power of relational algebra. Such a restriction is of particular interest in the context of logic and databases because it allows a direct access to relational databases through the logic programming language and therefore does not require an extra language for accessing the database.

In practice, this results in application programs which use the restricted logic programming language for accessing relational databases, and which use the unrestricted logic programming language for the application itself.

For each data object of the relational database model there is an appropriate construct in the logic language:

- A *domain* corresponds to a set of constants,
- A *relation table* corresponds to an extensionally defined *predicate*, i.e. a set of facts.
  The relation name is mapped to a predicate symbol, the number of attributes is equal to the arity of a predicate, and each relation attribute is mapped to a predicate argument via a mapping function. Attribute values are atomic constants, i.e. they have no internal structure.
- A *database query* corresponds to a non-recursive *goal*.

Note that in actual implementations of a logic programming language the order of tuples in a relation may be significant, whereas in relational database systems no particular order of records is assumed. Consequently, if a logic program is to access data stored in external relational databases, it must be guaranteed that the order of database records is of no relevance to the logic program.

2.3.2 Representation of relational algebra in the logic programming language

Any operation of the relational algebra can be represented through Horn clauses. It is a straightforward task to translate a relational algebra operation into an equivalent clausal form via the relational calculus expression for the algebra operation.

A special predicate, called *answer* or *result predicate*, is introduced to denote the relational expression that is defined [Green 69]. This answer predicate consists of one or more rules with the same predicate name and arity. The rule head is used to express projection, and the body expresses the other relational operators. Note that it is always possible to define an answer predicate for a relational expression because projection can always be pulled out of the expression and applied after all other operations have been evaluated.

Example

The union of two union-compatible relations `R` and `S` with `n` attributes is defined as follows:

$$R \cup S := \forall x: x \in R \vee x \in S$$

Because the union operation is to be represented as a clause the answer predicate will be named `union` with arity `n`. The relational calculus formula on the right side of the definition can be directly represented in the clause body:

$$union(X_1,...,X_n) :- r(X_1,...,X_n) ; s(X_1,...,X_n).$$

♦

The logic programming language representations for the six primitive relational operations are given below. This presentation follows the one presented in the book by Maier and Warren [Maier/Warren 89] with slight modifications.

The relational algebra operations union, intersection and difference are straightforward translations from the operation definition in relational calculus. For these three operations both relations involved must be union-compatible. Union-compatibility is expressed in the logic language through having the same variable arguments in both literals representing the relations.

- `union(X,...,Z):- r(X,...,Z); s(X,...,Z).`
  expresses $R \cup S$ through a disjunction of positive literals in the clause body:
- `intersection(X,...,Z):- r(X,...,Z), s(X,...,Z).`
  expresses $R \cap S$ through a conjunction of positive literals in the clause body:
- `difference(X,...,Z):- r(X,...,Z), not s(X,...,Z).`
  expresses $R \setminus S$ through a conjunction of a positive and a negative literal in the clause body:

Note that in a logic language based on negation as failure variable bindings made inside the negated literal are undone upon termination of the evaluation of the literal. For safe negation, all arguments of a negated goal must thus be bound when the goal is called. In the above formulation of difference the positive literal `r(X,...,Z)` must be evaluated first to bind the variable arguments. The subsequent negated literal `not s(X,...,Z)` can then be evaluated safely.

The representation of the relational algebra operations selection and join is only slightly more complex. Let {X,...,Z} denote the set of variable arguments of a literal, each $Y \in \{X,...,Z\}$ corresponding to an attribute of the appropriate relation.

- Join

  ```
  join(P,...,R,X,...,Z):-r(P,...,R),s(X,...,Z),Q1 θ Y1,...,Qn θ Yn.
  ```

  where $Q_i \in \{P,...,R\}$ and $Y_i \in \{X,...,Z\}$ expresses the join R [R.W θ S.W] S. The head of the clause consists of a concatenation of arguments from R and S. In the body, calls to r and s bind their arguments, and the join condition θ is expressed explicitly through a sequence of comparison operations of the appropriate variables.

  The natural join R [R.W = S.W]may be expressed through shared variables

  ```
  nat_join(P,...,R,X,...,Z):- r(P,…,R),s(X,…,Z).
  ```

  where $W \subseteq \{P,...,R\} \cap \{X,...,Z\}$

- Selection

  ```
  selection(X,...,Z):-r(X,…,Z),W = a.
  ```

  where $W \in \{X,...,Z\}$ expresses the selection $\sigma_{R.W=a}R$. In the body of the clause, the variable corresponding to the appropriate attribute is an argument of a comparison operation representing the selection condition.:

- Projection

  ```
  projection(X,...,Z) :- r(P,...,Q).
  ```

  where $\{X,...,Z\} \subseteq \{P,...,Q\}$ expresses the projection $\pi_{R.X…R.Z}R$. The set of variables in the head of the predicate is a subset of the variables occurring in the body of the predicate.

Complex relational expressions, such as nested expressions, can be formulated in the logic language through a complex answer predicate. The head of this answer predicate contains the variables corresponding to the attributes to be retrieved, while its body contains the literals corresponding to the individual subexpressions.

Example

The projection on the attributes `departure`, `destination`, `plane` applied to the result of a join over the common attribute `plane` of `Flight` and `type` of `Plane` is expressed in relational algebra as

$$\pi_{\texttt{departure,destination,plane}}\texttt{Flight[Flight.plane=Plane.type]Plane}$$

In the logic programming language this operation is expressed as the Horn clause

```
proj_join(Departure,Destination,Plane):-
  flight(FlightNo,Departure,Destination,Plane),
  plane(Plane,Seats).
```

♦

With a clausal representation of the relational algebra it is possible to formulate any relational query in a logic programming language. A restriction of the logic programming language to the above clauses results in the Horn clause equivalent of relational calculus, with the expressive power equal to that of relational algebra. Effectively, the language defined here corresponds to Datalog with negation, but without recursion [Ullman 88, Gardarin/Valduriez 88, Ceri et al. 90].

Part II

Concept

3

Coupled systems

A *coupled system* consists of a programming language system connected to an external database system. The database is accessed prior to or during the evaluation of application programs written in the programming language.

In the remainder of this thesis, coupled systems are restricted to logic programming language systems coupled to external relational database systems.

3.1 General structure of coupled systems

The clauses of a logic program can be stored either internally in the logic language system workspace in main memory, or externally in a relational database system on secondary memory. A logic program in a coupled system may have a subset of its program clauses stored internally, and the rest of the clauses stored externally in a relational database system.

- A *program predicate*, or simply *predicate* if the reference is clear from the context, is a predicate the clauses of which are stored internally in the logic language system workspace.
- A *database predicate* is a predicate the clauses of which are stored in an external database.

Note that — with the exception of comparison operations and arithmetic functions — a predicate must either be a program predicate or a database predicate, but not both. This is no restriction since a predicate p that violates this condition can always be redefined through renaming the externally stored definition to p´ and adding a call to p´ to the definition of p [Bancilhon/Ramakrishnan 86].

The standard comparison operators for constant values, e.g. “>”, “<“, “=” etc., can be thought of as relation tables with two attributes corresponding to the operands. n-ary arithmetic functions can be thought of as n+1-ary relation tables with n attributes for the operands and one result attribute. Comparison operations and arithmetic functions are thus database predicates as well as program predicates.

- A *database fact* is an extensionally defined database predicate.
- A *database goal* is a clause with an empty head which contains in its body only calls to database predicates.
- A *base conjunction* is a conjunction of database goals.

Any sequence of database goals can be split into disjunctions of base conjunctions.

In coupled systems a complex goal may contain both goals and database goals in any order. For efficiency reasons it is desirable to achieve as long as possible base conjunctions. This is always possible through reordering program goals and database goals [Ceri et al. 90].

3.1.1 Embedding vs. integration

In his thesis on embedding database access into high-level procedural programming languages, Bever [Bever 86] discerns two basic methods of coupling a database system with a programming language system: integration vs. embedding.

- *Integration* means that the programming language system is extended to incorporate database system features. Integration requires extending the programming language through database language constructs, and entails modifications of the programming language compiler and the runtime system.
- *Embedding* means that the database access is implementable entirely through language constructs provided by the programming language. Embedding database access into a programming language allows the programming language and the database language to be chosen independently, and does not require modifications of the programming language compiler.

He defines two forms of embedding: *type embedding* (Typeinbettung) and *language embedding* (Spracheinbettung).

Type embedding is schema dependent since only the current database schema is represented by datastructures of the programming language. Language embedding is schema independent, and the database language itself is represented by programming language constructs. An instance of a language embedding, the representation of an actual database schema, is thus a *concretization* of the abstract language embedding.

Bever lists the following requirements for the embedding of database access into programming languages.

- Independence of database language and programming languages
- No modification of the programming language compiler
- Database type and view definition also by the programming language
- Static type checking

- Programming language representation of data objects not in the responsibility of the application programmer
- Orthogonality
- Prevention of redundant tests in the database system.

Clearly, these requirements are coined for procedural programming languages. For logic programming languages these requirements have to be modified:

- Logic programming languages are often untyped languages, and the database access language is a sublanguage of the logic programming language.
  Type checking for accessing the database or retrieving data is thus not always feasible in untyped languages.
- In logic programming languages there is no distinction between program and data: program clauses are terms. This allows the dynamic definition of database access in the logic programming language itself.
  Static analysis of database access is not sufficient. Instead, database access requests and the data retrieved from the database system must be interpreted.
- Furthermore, the dynamic properties of logic programming languages allow language extensions without modifications of the language compiler.

The distinction of embedding an integration gives a rather general characterization of coupled systems. It relates to the database system and the logic programming system as a whole and is not specific enough to capture the system architecture nor the system languages.

3.1.2 Physical and logical level

In his discussion of coupled systems Bocca [Bocca 86] separates language issues from system architecture issues. He distinguishes between a *physical level*, which relates to the system architecture of a coupled system, and a *logical level*, which relates to the system languages.

Bocca uses the terms *integration* and *coupling* to describe the degree of coupling on the physical level, and *close coupling* and *loose coupling* for the logical level.

In his terminology, *integration* means that a database system and a logic programming language are integrated in one single system. *Coupling* means that both systems run independently of each other. A *closely coupled system* is a system in which the programming language is also the data manipulation language of the database. A *loosely coupled system* is a system in which the programming language and the data manipulation language are different languages.

In this thesis, I prefer to use *loose* and *tight* for both the logical and the physical level because these terms adequately reflect the fact that there is a smooth transition from integration to coupling on either level. In the following, a coupled system is thus always described by giving the degree of coupling on both levels as in “*physically loosely and logically tightly coupled system*”.

3.1.3 Description of coupled systems on the physical level

On the physical level a coupled system is characterized through its basic components

- logic programming language system,
- database system, and an
- interface between the logic programming language system and the database system.

Logic language system

The logic programming language system implements the evaluation of logic programs. An evaluation is determined through its granularity and its control strategy.

The *granularity* of an evaluation is either a single tuple or a set of tuples. In systems based on SLDNF resolution, the evaluation strategy is tuple oriented — or *tuple-at-a-time* — because at most one instantiation of a clause from the resolvent is considered as the next goal to be solved. In systems based on set evaluation, the evaluation strategy is set oriented — or *set-at-a-time* — because a set of tuples is taken as the goal to be solved next.

The *control strategy* is determined by the computation rule and the search rule. The *standard control* strategy of SLDNF resolution based systems is to evaluate the clauses in the order as specified through the program code, select the left-most goal from the resolvent and proceed in a depth-first manner. More refined control strategies are *dynamic reordering* of the subgoals in the body of the currently selected clause, *delayed evaluation*, under which the evaluation of a goal may be postponed until specific conditions are met, or *co-routining*, under which more than one goal is evaluated at a time.

Database system

The database system implements the basic database functions of access to the database and data retrieval. Härder in [Härder 87] proposes a model of database systems which distinguishes five layers, each with its own interface to the outside world (Fig. 2.):

Access to a database system is possible on different levels. Users access database systems via *high-level declarative* database languages via the set interface. Host languages access a database system via a programming language interface which generally is either the record or the internal record interface. Programming language interfaces are tailored to specific classes of programming languages, and feature either *procedural* or *low-level* language access to the database.

The retrieval granularity depends on the interface through which the database system is accessed. For the user interface the retrieval granularity is an *entire relation* as a whole, whereas for the programming language interface the retrieval granularity is a *single record*.

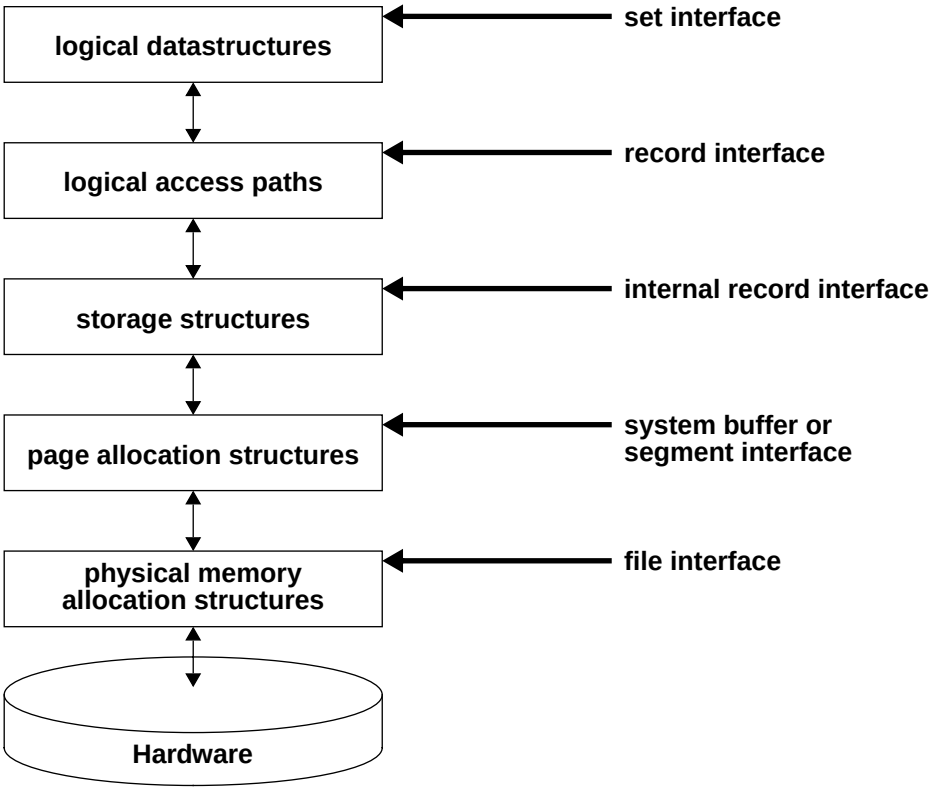


Fig. 2. Five layer model of a database system implementation

3.1.4 Description of coupled systems on the logical level

On the logical level a coupled system is characterized through the languages that are available

- the application programming language,
- the language(s) of the database system, and
- the database access language.

In this thesis the application programming language is a logic programming language.

The language of a database system can be subdivided into a data definition language and a data manipulation language. The data definition language is used to define the structure of a database. The data manipulation language consists of a query, an update, and a transaction language.

The database access language is the language used in the logic programming language to express access to the database system, and which provides the necessary datastructures to hold the data retrieved from the database system.

3.1.5 Database access procedure

The general database access procedure is as follows: The logic language system issues a database access request to the database interface in the logic programming language system. The request is transmitted through a communication channel to the appropriate interface of the database system. The database evaluates the database access request and returns the result of the evaluation through the communication channel to the logic programming language system where it is placed in a datastructure in the application program.

In coupled systems database access is possible either by a pre-processor or at load-time *before* the evaluation, or at runtime *during* the evaluation of an application program. In standard terminology the terms *static* and *dynamic* are used for access at load time and access at runtime respectively.

With *pre-processor database access* the application program is scanned for database predicates by a pre-processor before the evaluation of the program. The relation tables corresponding to the database predicates are then added to the application program through the assertion of new clauses.

With *static database access* database goals must be defined at load time already. An access path for these database goals is then established by the loading mechanism of the logic language system, and data is retrieved from the database system at runtime.

With *dynamic database access* the database system is accessed only upon the occurrence of a database predicate during the evaluation of the logic program. Generally, dynamic database access is achieved through the translation of database goals to the query language of the database system at runtime.

3.2 Interface

On either level there exists an interface between the logic programming system and the database system. This interface is determined by the type of coupling, integration or embedding.

On the physical level a general interface provides the basic functionalities

- communication,
- data conversion,
- database access, and
- coordination of evaluations.

On the logical level the interface is defined by the

- database access language, and the
- mode of database access.

3.2.1 Physical level interface

The communication channel connects the logic programming system to the database system. In physically tightly coupled systems this communication channel is an internal system bus. In physically loosely coupled systems the communication channel may be an operating system device such as a pipe or a stream.

Data conversion translates from one low-level data representation to another. In physically tightly coupled systems there is in general no need for a data conversion mechanism because the logic programming component and the database component use the same data. In physically loosely coupled systems the logic programming language system and the database system each access their own data, and the exchange of data necessitates data conversion. Generally, the exchange of data is restricted to such values that can be represented in both systems.

The database access mechanism implements the database access and the data retrieval via the database interface. For procedural database access via the internal record interface this requires access to low-level information in the database system dictionary, e.g. internal relation or attribute names, or the position of attribute values in records. Procedural access via the record interface requires the creation and use of a database cursor. For non-procedural database access the database is accessed through queries formulated in the database query language.

The coordination mechanism monitors the flow of control and coordinates the programming language and the database system evaluations. Two cases can be distinguished: either the granularity of the logic language evaluation and the retrieval granularity of the database system are the same, or they are different. In the first case the coordination mechanism simply passes the data retrieved from the database system on to the logic language system. With different granularities, relations retrieved from the database system are stored in temporary buffers, pipes, or files from which they are returned to the logic language a tuple at a time.

3.2.2 Logical level interface

The database access language within the logic programming language is either an *extension* or a *sublanguage* of the logic programming language. In the first case, special constructs are introduced into database goals for accessing the database, e.g. relational algebra operators, or existing datastructures are given a new semantics, e.g. atoms which represent a database query. In the second case, the database access language consists of the logic programming language restricted in such a way that it is equivalent in expressive power to the database language.

In *single relation access* only one relation table can be accessed through a database goal, whereas in *view access* multiple relation tables can be accessed. With single relation access only the relational algebra operations selection and projection can be directly evaluated in the database system. Any other relational operation has to be implemented on top of this single relation access in the logic programming system. With view access in principle any relational algebra operation can be directly evaluated in the database system.

The expressive power of the database interface may be different on the database and on the logic programming side. It is possible that the logic language allows expressions that the database system does not understand, e.g. recursion or compound terms as arguments. Conversely, there may be database language expressions that the logic language cannot express and thus cannot make use of in its access to the database, e.g. transaction control commands. This situation is described in Fig. 3. (adapted from [Bever 86]):.

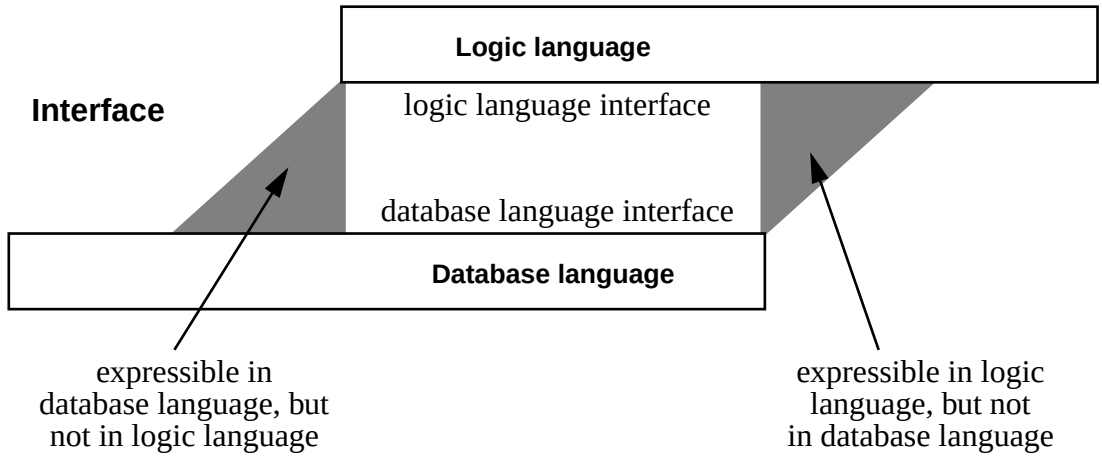


Fig. 3. Logical interface

4

Framework for coupled systems

Coupled systems can be classified by their structure, and a general description of their properties can be given through a set of qualitative criteria. The structure of a coupled system is given by the degree of coupling on both the physical and the logical level. On either level any degree of coupling is possible, ranging from loose to tight coupling.

In this chapter I develop a two-dimensional framework and a set of criteria for the classification of coupled systems according to the degree of coupling on both levels. With this framework, it is possible to derive the general properties of a coupled system from its position in the matrix.

4.1 Two-dimensional framework

Various frameworks for the classification of approaches to coupled systems have been proposed. These frameworks capture the direction of development of a coupled system [Ioannides et al. 87, Gallaire 86, Jasper 90], they distinguish between compiling and interpreting systems [O´Hare/Sheth 89], or between integration and embedding [Bever 86].

Frameworks of the first class in general distinguish four basic types of coupled systems (terminology from [Ioannides et al. 87]):

- Type 1: An existing logic programming language is enhanced with database functionality.
- Type 2: An existing database system is enhanced with inferential capabilities.
- Type 3: A system is built from scratch.
- Type 4: A logic programming system is used as a front-end to a database system.

This framework describes coupled systems by the way in which they were built. Such a historical view is inadequate for the classification because there is no direct relationship between the system development history and the system architecture or language.

The compiling/interpreting framework features an axis ranging from interpreting systems, in which a goal is evaluated immediately when it is encountered, to compiling systems, in which a program is analyzed before its evaluation. This framework contains a set of criteria that are used to represent the characteristic properties of a particular approach to coupled systems. These criteria may be descriptive, such as database access or language evaluation granularity, or qualitative, such as system efficiency and implementation effort. The main drawback of this framework is that it classifies systems as being very similar due to their proximity on the compiling/interpreting axis which are in reality totally different approaches to coupled systems.

The two-dimensional framework is based on the physical and the logical level identified above. Because the logical and the physical level are independent of each other a matrix can be established with each level corresponding to one axis. Both axes are labelled with *loose* and *tight* for the degree of coupling. Shaded lines serve to mark the middle of the range between loose and tight on both axes.

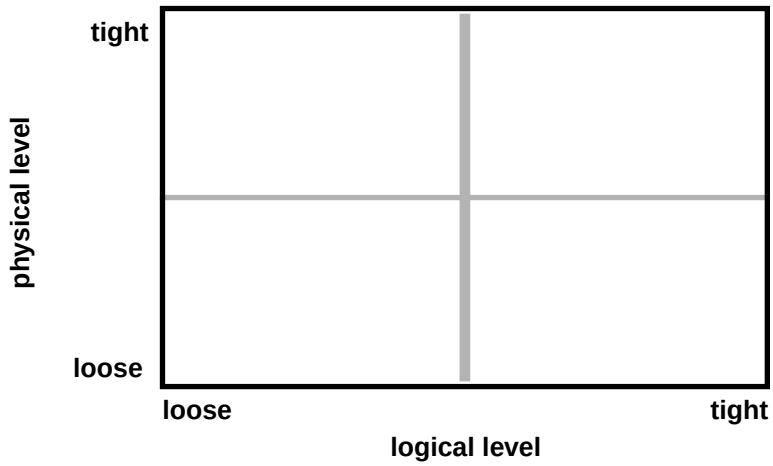


Fig. 4. Matrix of logical vs. physical level framework

This matrix distinguishes four basic types of coupled systems which correspond to the four areas delimited by the shaded lines in Fig. 4.

- *physically and logically loosely coupled systems,*
- *physically tightly and logically loosely coupled systems,*
- *physically and logically tightly coupled systems,* and
- *physically loosely and logically tightly coupled systems.*

Specific architecture and language characteristics have to be chosen according to which different approaches to coupled systems can be positioned in the matrix.

The type of access to the database is directly related to the degree of coupling on the physical level. Non-procedural access to the database is typical of physically loosely coupled systems because the both the logic language system and the database system are separate processes and the data manipulation language of the database system is used for exchanging data. Low-level procedural

access is typical of physically tightly coupled systems because the physical allocation of data is known to both the database component and the logic language component of the system. Language access to the database via database cursors lies in the middle between procedural and non-procedural access.

On the logical level, loosely coupled means that the database language is a distinct language of its own. This is the case for extensions to the logic programming language. In logically tightly coupled systems the database access language is a sublanguage of the logic language featuring dynamic query formulation and view access to the database. In the middle there lie systems with a database access language in which language extensions are mixed with the logic language, e.g. in static database access definitions.

The relationship between architecture and language characteristics and the two-dimensional framework is shown in Fig. 5.

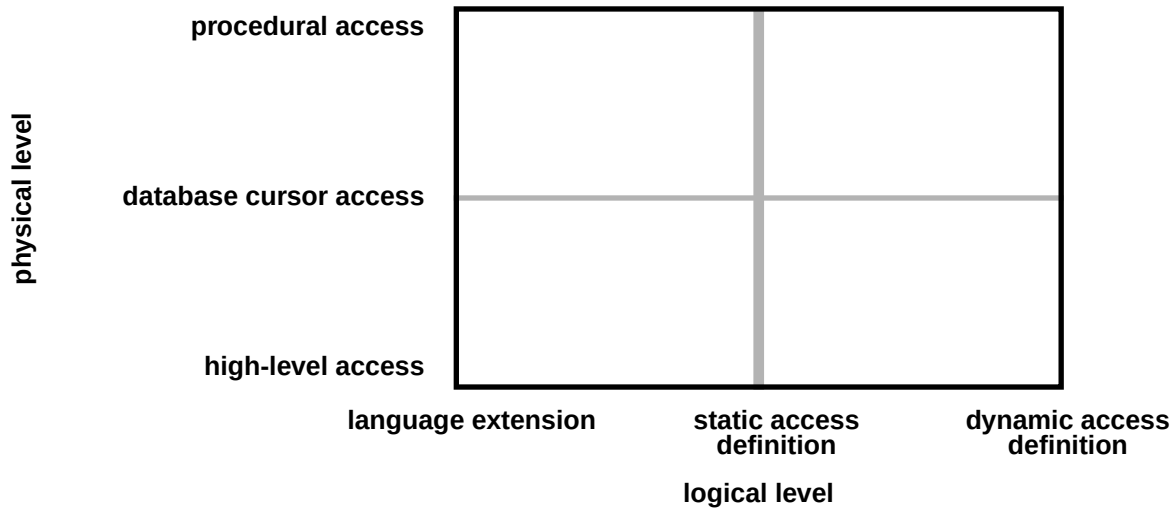


Fig. 5. Architecture and language characteristics

4.2 Qualitative criteria for coupled systems

The two-dimensional matrix allows to distinguish different approaches to coupled systems by their structure. However, in order to capture the characteristic properties of a particular approach, qualitative criteria are needed. Ideally, there should exist a close correspondence between the matrix position of a coupled system and its characteristic properties.

In this thesis a set of five qualitative criteria is proposed. The three criteria on the physical level are

- *efficiency,*
- *implementation effort*, and
- *independence of the database system.*

On the logical level there are two criteria:

- *expressive power* and
- *naturalness*.

4.2.1 Efficiency

Efficiency captures the overall system efficiency which is determined to a large extent by the data throughput of the interface between the logic language and the database system. This data throughput is determined by the way in which data is transferred between the database and the logic language, and by the amount of administration between the evaluation strategies of the system components.

Generally, efficiency is high in physically tightly coupled systems because there is no transport of data, no data conversion and only little administration overhead. Efficiency is low in physically loosely coupled systems because data has to be transferred from the database component to the logic language system and considerable overhead may be necessary for the conversion of data formats and the coordination of evaluation strategies.

4.2.2 Implementation effort

With *implementation effort* I denote the amount of work that is necessary to implement a coupled system. Only the effort for the implementation of the basic functionality of a particular approach is considered, but not any additional effort for optimizations.

The implementation effort for physically tightly coupled systems is high because a new compiler and a new runtime system for an integrated logic programming system with database access has to be built. In general, integrated systems have to be built from scratch. Implementation effort is low for physically loosely coupled systems because in general existing subsystems only have to be connected to each other via a communication channel. Depending on the type of database access, modifications of the evaluation mechanism of the logic language may be necessary.

4.2.3 Independence

With *independence* the ability to connect a logic language with arbitrary relational database systems is denoted. Obviously, different relational databases can only be accessed with high-level non-procedural database access using the data manipulation language of the database system.

Physically loosely coupled systems thus have a high independence because with a suitable translation of database requests any relational database can be accessed. Independence is low in physically tightly coupled systems because only the built-in database component can be accessed.

4.2.4 Expressive power

The overall *expressive power* of a coupled system is determined by its most expressive component, which is, in general, the logic language. In section 2.3 it has been shown that the languages of

interest for coupled systems can be ordered hierarchically, with first-order predicate logic as the most expressive language, and Datalog and relational algebra with less expressive power. In theory, expressive power is thus independent of the degree of coupling on the logical level.

In practice, however, this does not hold. In logically loosely coupled systems the expressive power is low because there coexist two distinct languages. The syntax and semantics of both languages are different, and thus expressions of one language may not be representable in the other language. In logically tightly coupled systems expressive power is high because the database language is subsumed by the logic language.

4.2.5 Naturalness

Naturalness captures the ease of use and the appropriateness of a coupled system for a given application.

Naturalness is low in logically loosely coupled systems because different programming paradigms have to be respected. Writing an application program in two different languages leads to programs that are difficult to read and to understand. Naturalness is high in logically tightly coupled systems. Writing a system in one single language leads to well-designed and readable programs.

4.3 Summary

The set of qualitative criteria is used to characterize coupled systems. Each criterion is assigned a value. This value is directly related to a specific matrix position (Fig. 6.)

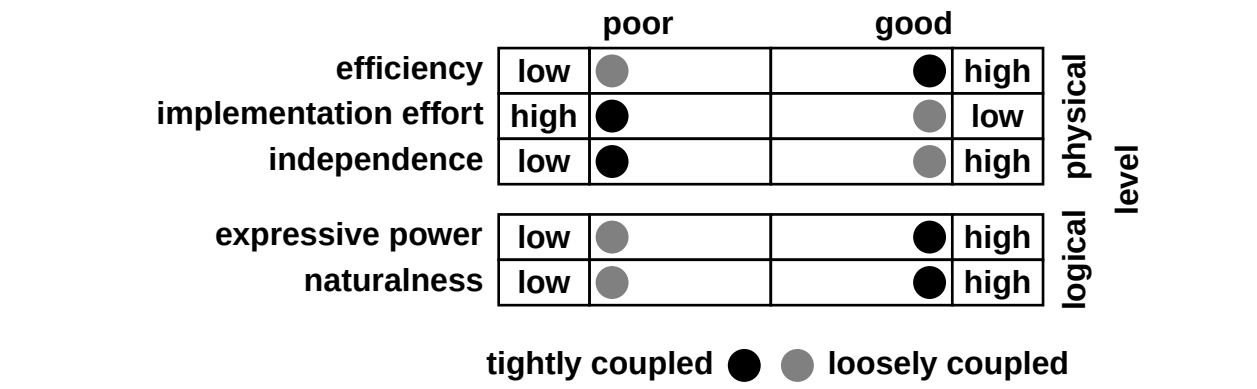


Fig. 6. Relationship between matrix position and values for qualitative criteria

From this table it follows that a physically loosely and logically tightly coupled system promises the best values for the characteristic criteria with the notable exception of efficiency. However, if the amount of data retrieved from the database system can be reduced through maximally restrictive queries, and if the data retrieved from the database system is handled efficiently, efficiency in physically loosely coupled systems is bound to improve.

Note that the values for the criteria represent theoretical values for a given approach to coupled systems. Any actual system implementation will have to be compared to these attainable values.

5

Application of the framework

In this chapter prototypical approaches to coupled systems that have been proposed in the literature are classified according to the two-dimensional framework. These approaches have been selected because they represent particularly interesting stages in the development of coupled systems.

5.1 Sample application

The example application consists of a flights and a planes database according to the following ER-diagram (Fig. 7.)

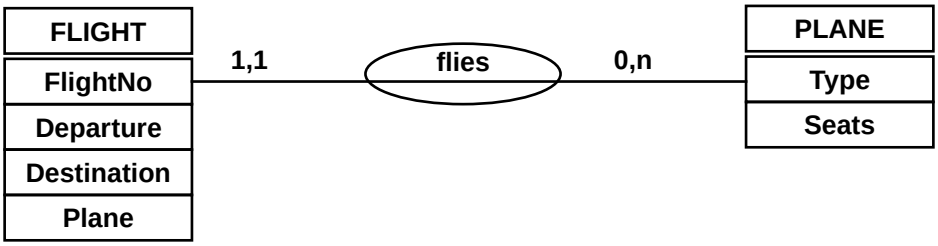


Fig. 7. ER-diagram of sample application

`Flight` is a relation with the four attributes `flightno`, `departure`, `destination` and `plane`. `Plane` is a relation with the two attributes `type` and `seats`. In Prolog this database can be represented through the database predicates `flight`/4 and `plane`/2 with the order of arguments corresponding to the order of relation attributes:

```
% flight(FlightNo,Departure,Destination,Plane).
flight(sw1,zurich,geneva,b-737).
...

% plane(Type,Seats).
plane(b-737,150).
...
```

5.2 PROSQL

PROSQL [Chang/Walker 86] connects a Prolog system with an SQL relational database system. Database predicates have the reserved predicate name `sql`/1. The only argument to an `sql`/1 clause is an atomic value that represents an SQL command.

In PROSQL database access is static, and database predicates must precede any predicates that operate on the data retrieved from the database:

```
?- sql(' SELECT FLIGHTNO, DEPARTURE, DESTINATION, PLANE
         FROM FLIGHT')
   flight(FNo, Departure, Destination, Plane).
```

When a database predicate is encountered the atom is transmitted to the database where it is interpreted as a query. The current Prolog evaluation is suspended until the result of the operation is returned. Any result relation is asserted into the Prolog workspace as a predicate under the name of the first relation in the from-part of a query. Only then any data retrieved from the database can be accessed by subsequent Prolog predicates.

PROSQL is a physically and logically loosely coupled system because Prolog and the SQL database system are separate processes that communicate with each other, and because two different languages are present in the system.

5.3 Quintus Prolog

Quintus offers a database interface for different database systems such as Unify or Oracle [Quintus]. Note that although I present only Quintus Prolog here most other commercial Prolog implementations offer a database interface similar to the approach of Quintus Prolog.

The database access of Quintus Prolog is both static view and static single relation access. Update access is allowed through reserved predicates.

Single relation access is defined through the predicate `db`/3. The third argument of `db`/3 defines a mapping from a Prolog term to a relation table. A `db`/3 fact must precede any access to an external database:

```
db(flight,example,flight(
  'FLIGHTNO':string,
  'DEPARTURE':string,
  'DESTINATION':string,
  'TYPE':string)).
```

The actual database access follows Prolog syntax and operational semantics. The goal

```
?- flight(FlightNo, Departure, Destination, Plane)
```

is a legal database goal.

View access is defined by an explicit mode declaration followed by a rule. This rule contains in its body only database predicates, i.e. single relation access predicates, and arithmetic predicates. The arguments in the head express projection on the relation attributes:

```
:- db_mode capacity(+,+,-,-).

capacity(Departure,Destination,Plane,Seats):-
  flight(_,Departure,Destination,Plane),
  plane(Plane,Seats).
```

Both for single relation access and for view access the corresponding query is evaluated in the database system using the standard set-oriented evaluation. The result relation is accessed a tuple at a time by the Prolog system via database cursors.

Quintus Prolog with its database interface implements a physically rather loosely coupled system. It is not a true loosely coupled system because database cursors are used which are in fact a procedural data retrieval mechanism.

Although the logic language is very close to standard Prolog syntax and semantics, Quintus Prolog is not a true logically tightly coupled system. The underlying database language shows through in the distinction of relation and view access which statically define the access to the database, in explicit mode declarations for view access, and in the special syntax of the aggregate functions with a reserved predicate name.

5.4 CGW and PRIMO

CGW, developed by Ceri, Gottlob and Wiederhold [Ceri et al. 87, Ceri et al. 89], couples a Prolog system with a relational database system. The primary design objective was to achieve high efficiency by never repeating the same database request. For this the technique of query subsumption was developed.

In CGW, the database can be accessed either through a pre-processor, or statically. In both cases, only single relations can be accessed, and database access is procedural in that it directly addresses physical pages in the database system. Database access is read-only.

The pre-processor detects database predicates in the program code through the use of a dictionary that contains the mapping from relation tables to Prolog predicates. The corresponding database relations are either loaded directly into the Prolog workspace, or they are accessed during the evaluation of the program. The decision whether to directly load relation tables or to postpone database access requires sophisticated statistical information about the database contents, such as the number of records in a table and the number of different values for the relation attributes.

Repeated evaluation of the same database requests is prevented through query subsumption. Query subsumption can be performed efficiently for single literals, but it requires bookkeeping about the previous interaction with the database system. Special tracer predicates are used in CGW to record the state of any database request.

Before actually accessing the external database, this tracer predicate is checked to find out whether the current database request — or a more general one — has already been answered. If so, a fact

```
queried(database_predicate).
```

exists in the workspace, and the corresponding relation is already stored in the workspace where it can be accessed by the Prolog system. If the current database request has not yet been fully evaluated a tracer fact contains the address of the last page that has been read in:

```
tracer(database_predicate,current_db_page).
```

The request is evaluated in the database system and the results of the evaluation are asserted into the Prolog workspace. A new tracer fact with the address of the most recently fetched database page is asserted into the workspace.

Query subsumption implies that part of the extension of a predicate is already in the workspace, and that further clauses are added during the evaluation. These clauses must be accessible immediately for the evaluation to be correct. However, this violates the logical update principle [Lindholm/O'Keefe 87] which states that a predicate may not be modified while it is being accessed to prevent unpredictable program behavior.

Because of its low-level procedural access to the database, CGW is a physically rather tightly coupled system. It is not a true logically tightly coupled system because tracer predicates are visible and because database access is defined statically.

PRIMO [Gozzi et al. 90] is a successor system to CGW. Its main design objective has been to provide a portable Prolog - database coupling through modules. PRIMO connects any Prolog system with any SQL database system provided that the Prolog system has an interface to the operating system. Query subsumption is retained from CGW, and access to a maximum of two relations for join-operations is included.

PRIMO is a physically loosely coupled system because database access is non-procedural using the SQL query language. However, it is not a true logically tightly coupled system because the reserved predicate name `retrieve` must be used for database access, because tracer predicates are visible, and because database access is defined statically.

5.5 KB-Prolog

KB-Prolog [Bocca et al. 89 a] integrates a Prolog system with the grid-file database system BANG [Freeston 88]. In KB-Prolog, relations are considered to be primitive datastructures.

Database access in KB-Prolog is static, and database updates are allowed. Two different database access methods exist, relational algebra and a retrieval predicate with the reserved name `retr_tup`/2.

Relational operators are defined as infix operators, e.g. :*:/2 for the join operation as in

```
capacity isr flight :*: plane where flight^plane == plane^type
```

Note that relational algebra may only be used for the definition and manipulation of relation tables, but not for data retrieval. This is only possible through `retr_tup`/2, which returns one tuple at a time as a list in its second argument:

```
retr_tup(flight,[FlightNo,Departure,Destination,Type]).
```

The relational algebra in KB-Prolog is a non-logical extension to Prolog. The database modification operators such as `isr`/2, `<++`/2, or `<--`/2 that create a relation, or add or delete a list of records, are in fact destructive assignments which violate the referential transparency of logic programming. In KB-Prolog it is perfectly legal to do the following:

```
X isr flight,
flight <++ [(sw2,zurich,geneva,b-737)]
X isr flight
```

where the binding of `X` before and after the update is the same relation named `flight`, although this relation has been augmented by one record.

KB-Prolog is a physically tightly and logically loosely coupled system because the database is truly integrated into the system, and because there are in fact three languages in the system: Prolog, relational algebra, and the specific database retrieval predicate `retr_tup`/2.

5.6 System by Nussbaum

The system by Nussbaum [Nussbaum 88] integrates a database and a logic programming system with a bottom-up set-oriented evaluation strategy. In this system, database access is delayed as long as possible through reordering goals to result in highly restrictive queries. Collecting database accesses results in complex queries which strongly restrict the data to be selected in the database and it reduces the total number of database accesses. Database access is dynamic and read-only view access.

The system language is a subset of Horn clause languages with only linear recursion, a restricted form of functions, and no negation. There are no special database predicates, access to the database is thus integrated into the logic language.

Because of the integration of database and logic language system, the system by Nussbaum is a true physically tightly coupled system. It is also a logically tightly coupled system because database access is completely invisible.

5.7 Prolog-SQL coupling by Danielsson and Barklund

The Prolog-SQL coupling of M. Danielsson and J. Barklund [Danielsson/Barklund 90] uses the special symbol “|” to enclose database goals in otherwise regular program clauses:

```
high_capacity(From,To,Type,Seats):-
  |flight(No, From, To, Type),
   plane(Type,Seats),
   Seats > 300 |.
```

Note that comparison operations may appear inside the vertical bars.

Database access is statically defined view access. Database goals are normalized to base conjunctions to result in highly restrictive queries. These base conjunctions are translated to SQL and evaluated in the database system. The result relation is returned to Prolog one record at a time through the use of database cursors.

The system of Danielsson is not a true physically loosely coupled system because of the retrieval through database cursors. It is not a true logically tightly coupled system either because database access definition is static.

5.8 EKS-V1

EKS-V1, developed at the ECRC [Vieille et al. 90], is a knowledge based system integrated into the Megalog Prolog system [Bocca et al. 89 b]. Besides its deduction capabilities, EKS-V1 features maintenance of integrity in the database, and supports pre- and postconditional updates and hypothetical reasoning.

The database access language is an extended Datalog with existential and universal quantifiers, aggregate functions and evaluable predicates.

```
reachable(Destination) ->
  exists [Departure]:
  flight(_,Departure,Destination,Plane)
  -> plane(Plane,_).
```

The reserved predicate `find`/1retrieves the set of answers from the database:

```
find reachable(Destination).
```

EKS-V1 implements a set-oriented top-down evaluation. Evaluable predicates are implemented as calls to externally defined procedures or predicates, e.g. defined in Prolog or C.

EKS-V1 is a physically tightly coupled system because both the database system and the Megalog system run as one process. It is also a logically tightly coupled system because the same language is used for database access, the formulation of integrity constraints, and the procedural extensions such as updates.

5.9 Other work

There is a variety of related work that I have not included in this overview because of different research goals. [Li 84] has implemented a database system entirely in Prolog. [Kühn 89] uses Prolog for the implementation of a heterogeneous database system.

DedGin* [Vieille/Lefêbvre 89] translates Datalog queries into query execution graphs which serve as a global bookkeeping mechanism to avoid non-terminating searches. Query execution graphs can be evaluated directly in the database system. For recursive programs the query execution graph is cyclic and it consists of series of projections and joins over temporary relations. Cyclic execution graphs are evaluated in iterations. The iteration continues until no more new records are generated.

LDL [Tsur 88, Chimenti et al. 90, Zaniolo 90] is a knowledge base system that is based on first-order logic. Its main features are safe negation and sets as primitive datastructures. So far, LDL has only been implemented as a prototype system without an external database system. LDL considers itself to be not a coupled system, but a totally new and fully declarative programming language.

Quite the opposite goal is pursued in KBL [Manthey et al. 89]. KBL is a knowledge base language that strictly separates procedural from declarative aspects. This clear distinction is necessary to express the different semantics of a command, e.g. a print command, and those of a logical expression, e.g. a condition.

PROTOS-L [Böttcher 89] is a coupled system in which entire programs are stored externally. The language used is Prolog without the dynamic database update commands `assert`/1 and `retract`/1, but augmented through types and modules. Programs stored externally are considered as modules, and through the module interface the predicates defined in the module can be accessed.

LogiQuel [Marti et al. 89] is a coupled system based on Datalog with negation, extended through dynamic database updates. LogiQuel may be considered as a front-end to relational database systems. The evaluation of LogiQuel programs consists of translating the programs to SQL queries and evaluating these queries in the database system. The evaluation of recursive rules is implemented following the naive and the semi-naive bottom-up [Bancilhon/Ramakrishnan 86] strategies. LogiQuel is implemented in Modula-2 and accesses an external Oracle SQL database system.

In [Hansen et al. 89] a relational database system is used to store only the common and application-independent knowledge. This data is extracted from application programs through some factorization process. An application program then only defines its own use of the data stored in the database system.

5.10 Application of the framework

The various approaches to coupled systems can be positioned in the two-dimensional matrix according to the system architecture and language characteristics defined in section 4.1. The matrix is shown in Fig. 8.

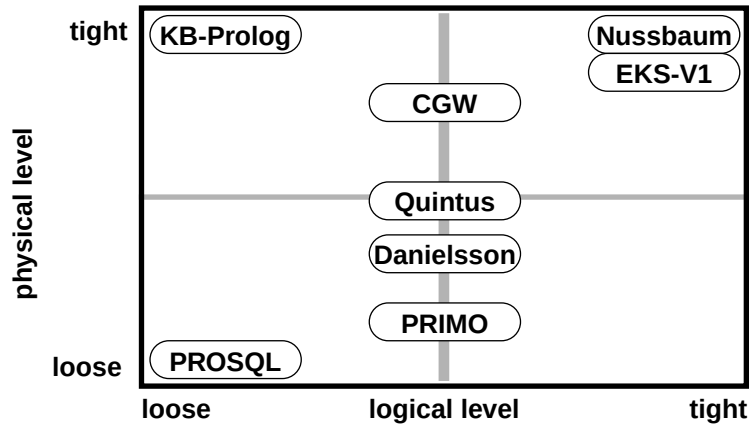


Fig. 8. Matrix positions of coupled system approaches

5.11 Discussion

The approaches to coupled systems in the previous sections were presented roughly in the order in which they were first published. From this chronological view two major development trends can be discerned:

- improving efficiency on the one side, and
- providing maximum independence on the other side.

Both trends are now discussed in detail.

5.11.1 Improving efficiency

The efficiency of a coupled system is to a large extent determined by the interface between the logical language system and the database system. Recall from section 3.2 that on the physical level the interface between the logic language system and the database system consists of the basic components coordination mechanism, communication channel and data conversion mechanism. On the logical level this interface consists of the database access language.

Physical level

Efforts to improve efficiency have concentrated on the physical level. Basically these efforts comprise a close cooperation of the evaluations of the logic language and the database system, and a minimization of data transmission and conversion.

Coordination of evaluation strategies

A coordination of evaluation strategies can be achieved in two ways: either through an explicit coordination mechanism in the interface, or by changing the evaluation strategy in one system component to match that of the other.

The development of techniques for the coordination of evaluations has been the following: from

- *asserting relations into main memory workspace* to
- *temporarily storing relations in buffers*, to
- *using procedural database access*, and finally to a
- *full integration* with a uniform evaluation strategy.

Asserting relations into main memory workspace

Asserting the extension of database predicates into the logic language workspace, also known as *cacheing of data*, effectively hides the database evaluation from the logic language system. The database evaluation returns a relation which is asserted as a sequence of program clauses into the workspace of the logic language. The evaluation of the logic language does not distinguish between such asserted clauses and other program clauses. Asserting result relations into the workspace is implemented in PROSQL, CGW and PRIMO.

Asserting relations in the internal workspace of the logic language is an extremely time and space consuming operation because clause indexes have to be updated and each clause has to be stored explicitly. A second problem is that assertions are not undone upon backtracking. Once memory is allocated it cannot be released automatically which almost inevitably leads to workspace overflow.

Buffering result relations

Buffers are operating system devices that temporarily store result relations. The rationale behind using buffers is that the database writes a whole result relation into the buffer at once, whereas the logic language system retrieves only one tuple at a time from the buffer. This approach is implemented in Educe [Bocca 86], which uses pipes as buffers, and in BERMUDA [Ioannides et al. 87], where temporary files are used.

The major problem of buffers is that their size and number is limited. If a buffer is too small to hold a relation, then either data is lost, or the database evaluation has to be suspended until the buffer has been emptied which causes administration overhead. If buffers are too big, valuable system resources are wasted. With only one buffer, subsequent database requests may overwrite the current buffer contents. Upon backtracking, the previous buffer contents cannot be restored and must be recalculated. Associating a proprietary buffer to each individual database request would in principle solve this problem. However, the number of buffers is always finite, and the number of database requests may exceed the number of buffers. This is especially true in recursive evaluations, where the number of recursion steps is not known in advance.

Procedural database access

Procedural access to the database system can be subdivided into low-level access via the internal record interface or even the segment interface, and access through database cursors via the record interface.

Direct access to relations via the segment interface has been implemented in CGW. Direct access returns to the logic language systems one physical page at a time, from which the requested records have to be extracted. This reduces the retrieval granularity from whole relations to physical pages which contain only a few records and only small amounts of data must thus be stored temporarily. The major problems of direct access are that the precision of retrieval is low because the position of a record on a particular page is independent of its attribute values, and that only single relations can be accessed.

Database cursors are retrieval mechanisms which are provided by relational database systems for high-level procedural programming languages. A database cursor provides a single-record interface for the retrieval of data from the database system.

In Quintus Prolog and the Prolog-SQL coupling by Danielsson each invocation of a database predicate is assigned a database cursor. The query corresponding to the body of the predicate is evaluated in the database system at the first call to the predicate. The current values of the cursor are returned via the argument variables of the database predicate. New values are fetched from the database upon backtracking, and the predicate fails when the cursor has reached the end of the result relation.

The major advantages of database cursors are that they are provided and supported by the database system, and that the granularity of data retrieval matches the granularity of the logic language evaluation. The main problem with cursors is that only a finite number is available in the database system which leads to similar problems as with using buffers. A second problem is that for the logic language evaluation mechanism the treatment of database cursors differs from that of internal pointers. The runtime system of the logic language thus has to be modified to incorporate database cursors.

*Full integrati*on

The previous techniques are employed when there are separate evaluations in both the logic language system and the database system. However, coupled systems are possible in which there exists a uniform evaluation. In such a system, database and logic language are simply subcomponents of a physically tightly coupled, or *integrated*, system. The evaluation in a physically tightly coupled system may either be tuple-oriented as in KB-Prolog, or set-oriented as in the system by Nussbaum or EKS-V1.

A uniform evaluation in a coupled system does not cause any coordination overhead and it is thus bound to be efficient. However, the implementation effort for a uniform evaluation is extremely high. Furthermore, a uniform evaluation strategy may directly affect the expressive power of a

coupled system. Currently only systems with languages of restricted expressive power, e.g. the system by Nussbaum, which is restricted to linear recursive languages without negation, or DedGin*, which is restricted to Datalog, have been implemented with a set-oriented evaluation strategy.

Communication channel

The effects of the type of communication channel that exists between the logic language system and the database system on the efficiency should be clear. The efficiency of the communication channel is determined by the transmission speed of the channel, and by the amount of data transferred through the channel.

The communication channel in coupled systems has evolved from an external slow channel between two distinct systems to a quick internal bus in physically tightly coupled systems. Efficiency can be increased by reducing the amount of data to be transferred. In PROSQL, whole relations are transferred. In Educe and MU-Prolog [Naish 87] the communication channel also serves as a buffer. In CGW only a few physical pages, and in Quintus Prolog only a few records need to be transferred in the best case. However, with a more sophisticated coordination of evaluations the ratio of control information versus actual data deteriorates.

Data conversion

In physically loosely coupled systems data conversion is always only necessary because different data formats are used in both the logic language and the database system. Data conversion is expensive, and it is thus desirable to have as little conversion as necessary. The data conversion mechanism is thus best situated only on one end of the communication channel, either in the logic programming language system or the database system. In the systems presented above, the data conversion component can be found on the logic language system side.

In physically tightly coupled systems there is in general no need for a data conversion mechanism because the same data is accessed by the database and the logic language component.

Logical level

The interface on the logical level also has a great effect on the efficiency of the coupled system as a whole. Two main contributions to improving efficiency can be discerned,

- query restriction, and
- language integration.

Query restriction

Query restriction depends on the database access language and the dynamic aspects of database access definition. In PROSQL queries are part of the program code. Because SQL statements are included as atomic constants in the application program queries cannot be restricted dynamically. A next step is to propagate variable bindings and constant values to the database system. This propagation of variable bindings is currently supported in most coupled systems, either with single relation or with view access.

Single relation access in general is not powerful enough to effectively restrict queries. In the following example with `employee`/2 as database predicate

```
retrieve(Person):-
  employee(Person,Salary),
  Salary < 100.000.
```

all records are retrieved, although only a few database records satisfy the comparison. In Educe conditions are allowed as extra arguments to database goals to restrict queries.

With view access, the amount of data to be retrieved can effectively be reduced through relational operations such as difference, intersection or through exploiting join-selectivity. Furthermore it is possible to express selection conditions through comparison operations as in the example above.

Finally, with dynamic access definition, maximally restrictive queries are possible because not only the current variable bindings, but also additional information from the current state of the evaluation can be used. Currently, dynamic access definition has only been implemented in physically tightly coupled systems with delayed evaluation such as the systems of [Cuppens/Demolombe 86] or [Nussbaum 88].

Language integration

Language integration also contributes to efficiency. In logically loosely coupled systems, as in PROSQL or KB-Prolog, data manipulated by the database language is not directly accessible to the logic language system. In PROSQL, SQL commands are considered to be atomic constants by the Prolog system, and data has to be asserted into the workspace to be accessible to the application program. In KB-Prolog, relational algebra is used for the manipulation of relations, but to actually retrieve data a special predicate must be used. Thus, in both systems a shift between different language paradigms is necessary which reduces efficiency.

In systems in which database access is a sublanguage of the logic language such problems occur to a much lesser degree. However, the language restriction to single relation access, as in CGW or BERMUDA, or to two relations, as in PRIMO, forces the logic language system to perform evaluations that could have been done more efficiently in the database system, even to recompute relations. In general, this is true for any static database access definition.

Of the systems presented above, only EKS-V1, Quintus Prolog, and the system by Danielsson support aggregate functions, the latter two merely in a weaker form because grouping on attributes cannot be expressed. Only EKS-V1 can express higher-order constructs such as grouping, sorting, or structured attributes.

5.11.2 Maximum independence

The independence of a coupled system of a particular database system implementation is possible only through a non-procedural access to the database system. For this, two techniques have been developed, namely

- a modular interface to various database systems, or
- the translation of database requests to high-level database query languages.

Modular interface for database access

With a modular interface to the database system, an additional layer is inserted between the logic language system and the database system. This layer is implemented through an access module to the database system. With specific modules different database systems can be accessed. The actual access to a database system is then implemented in the corresponding module. This technique is employed in PRIMO, a variation of it is used in commercial Prolog systems.

The major problem of a modular interface is that this interface lies underneath the logic programming language. The implementation of a database access module thus requires knowledge about low-level implementation details of the logic language system. Furthermore, the interface module is in general implemented in a different language which requires further language interfaces.

Translation of database requests

The second technique translates directly from the logic language to a high-level database query language without an intermediate interface. Each time a database predicate is called, the corresponding goals are translated to a query or a sequence of queries in the database language. The actual database access is performed through an interface to communication devices in the operating system, streams, or through calls to externally defined procedures. Translating database predicates to SQL is done in the Prolog-SQL system by Danielsson.

The advantage of translation is that database queries can be formulated dynamically, and that the translation procedure itself can be written in the logic language. The major drawback is that a translation is necessary for every call to a database predicate, which may be rather time-consuming

5.11.3 Summary

From this overview of approaches to coupled systems the following two observations can be made:

- The predominant design objective in coupled systems, once their feasibility had been demonstrated, was to improve efficiency.
- Only recently, the independence of a coupled system of a particular database system has been given more weight.

Efficiency has been the primary concern in the development of coupled systems. Any improvements have been achieved through an ever tighter physical coupling of the logic language system and the database system. This has lead to physically tightly coupled systems, or, in the terminology of Bever, to an *integration* of a database system into the logic programming system.

A first consequence of this development is that with every step in the direction of a tighter physical coupling the implementation effort grows. A second consequence is that independence is lost because only the built-in database can be accessed.

Independence has been a design goal of its own only since about 1986 with the proliferation of commercial Prolog implementations and the definition of SQL as the standard database language. Independence requires that the logic language and the database system be separate systems, and that a particular implementation of a database system be replaceable by another one. This is only possible in physically loosely coupled systems. In addition to that physically loosely coupled systems may exploit the high functionality of current database management systems, such as multi-user access, and they allow easy access to data already stored in existing databases.

It has been shown that a database access language which is a sublanguage of the logic programming language contributes to the overall system efficiency because it allows maximal restriction of queries. It also contributes to achieve maximal independence, because with the database access language a sublanguage of the logic programming language there is no predilection for a specific database system. Logically tightly coupled systems thus combine high efficiency with independence.

5.12 Requirements for a new approach

The development of a new approach to coupled systems is motivated by the following observations:

- A powerful database access language is necessary to effectively combine the full capacities of database systems with the high expressive power of logic language systems.

  Hence, arithmetic functions, aggregate functions, structured attributes, and the application of higher-order control such as grouping or sorting must be expressible in the database access language.

- In current systems, efficiency has primarily been improved through tight physical coupling. Less effort has been devoted to the logical level although a tight logical coupling would allow the formulation of maximally restrictive queries and thus contribute to improve the overall efficiency.

  Hence, the database access language is to be a sublanguage of the logic programming language.

- Today many commercial or public domain databases store large amounts of information relevant to new applications. These database services are offered on a variety of machines and they allow access through high-level query languages.

  Hence, independence is a crucial requirement.

- Furthermore, it should be possible to access this information from existing systems and applications.

  Hence, the new approach must be implementable and downward compatible with existing logic programming language systems.

A physically loosely and logically tightly coupled system with the database access language a sublanguage of the logic language for efficiency, with set-oriented data retrieval to allow the application of higher-order control, and with non-procedural database access for independence is thus desirable.

6

Database Set Predicates

Set predicates are higher-order extensions of programming languages based on first-order predicate logic. They retain *all* solutions to a goal as a *set* (or a *bag*) of variable instantiations. This property will be exploited to extend the definition of set predicates to result in database set predicates.

Database set predicates extend the traditional set predicates with access to external databases. The basic concept of database set predicates is that the evaluation of the goal to be proved is performed by the database system, and that the result relation of the database evaluation is captured by a standard datastructure of the logic language. This way

- the set-oriented evaluation of database systems is embedded into the standard tuple-oriented evaluation of logic language systems, and
- the logic language itself is used for accessing the external database system.

Although only Prolog set predicates are presented, this discussion is not restricted to Prolog but applies to set predicates in general and other logic languages based on tuple oriented evaluation.

6.1 Set predicates

Set predicates were originally proposed and implemented by D.H.D. Warren [Warren 82] as higher-order extensions to Prolog.

With standard SLDNF resolution a solution, i.e. a variable instantiation, is returned as the result of a successful proof of a goal. The search for further solutions is initiated through forced failure after a solution has been returned to the top-level goal. However, because any variable bindings are undone upon failure of a goal, it is not possible to collect all solutions for a given goal without resorting to extra-logical or control predicates. This problem is overcome through *set predicates* – also called *all-solutions* predicates – which retain all solutions to a goal in a datastructure for further processing.

6.1.1 Set predicate definition

Set predicates are of the following form:

```
set_predicate(Template,Goal,Instantiations)
```

`set_predicate` is name of the predicate. In most Prolog implementations, `set_predicate` is `findall`, `bagof`, and/or `setof`.

- `Template` is a term.
- `Goal` is an arbitrary goal which may include control predicates, system predicates, extra-logical predicates, etc. Note that this allows set predicates to be nested.
  Variables in `Goal` may be explicitly quantified through the existential quantifier ^/2 which takes a variable as its first and a goal as its second argument.
- `Instantiations` is a list of template instances.

Example

In the goal

```
?- setof(Destination,
   Plane^flight(Departure,Destination,Plane),Destinations)
```

`Destination` is the template term, `Plane^flight(Departure,Destination, Plane)` is the goal argument with the existentially quantified variable `Plane`. `Destinations` is unified with a list that contains all instantiations of the template variable `Destination` which are solutions to the goal argument.

♦

6.1.2 Set predicate semantics

Set predicates must be called with the first two arguments partially instantiated terms, and the third argument an uninstantiated variable or an instantiated list:

```
set_predicate(+Template, +Goal, ?Instantiations).
```

If `set_predicate` is called with the third argument an uninstantiated variable, then this variable is instantiated with a list of template term instantiations computed by the successful evaluation of the goal argument. With the third argument instantiated, `set_predicate`/3 only succeeds if this argument is unifiable with the list of template instantiations as computed by the evaluation of the goal argument.

`findall`/3 on the one side and `setof`/3 and `bagof`/3 on the other side differ in their treatment of

- quantification and
- finite failure of goal arguments.

The difference between `setof`/3 and `bagof`/3 is that the list of variable instantiations in `setof`/3 is sorted and does not contain duplicate entries.

Quantification

In Horn clause languages, variables in a clause are considered to be universally quantified. Because the body of a clause consists of negated literals, variables that occur only in the body of a clause are said to be existentially quantified. The binding of such existentially quantified variables is of no interest outside of the clause.

In set predicates a variable is *free* if it is neither bound when the set predicate is called nor does it occur in the `Template`. `findall`/3 considers the free variables in `Goal` to be existentially quantified, whereas they are implicitly universally quantified in `setof`/3 and `bagof`/3.

Consequently, `findall`/3 yields only one list of template instantiations, whereas `setof`/3 and `bagof`/3 produce different lists of template instantiations for each binding of the free variables in `Goal`. This means that `findall`/3 is deterministic and fails upon backtracking, whereas `setof`/3 and `bagof`/3 attempt to compute the next solution with a different binding of the free variables.

Example

In the example database

```
flight(zurich, geneva, b-737).
flight(zurich, paris, a-320).
flight(zurich, london, b-737).
```

`findall`/3 produces the following results (forced backtracking through `;` after each solution):

```
?-findall((Departure,Destination),
   flight(Departure,Destination,Type),List).

List = [(zurich,geneva),(zurich,paris),(zurich,london)];

no more solutions
```

Contrast this to the result of

```
?-setof((Departure,Destination),
   flight(Departure,Destination,Type),List)

Type = a-320, List = [(zurich, paris)];

Type = b-737, List = [(zurich,geneva),(zurich,london)];

no more solutions
```

The variable `Type` in the goal argument of the two top-level goals is free. In `findall`/3 this leads to only one list being returned, regardless of the binding for `Type`. With `setof`/3 each binding for `Type` results in a separate list.

♦

Quantification information can be made explicit in `setof`/3 and `bagof`/3.

Example

With the variable `Type` existentially quantified `setof`/3 yields a sorted list that contains the same entries as computed by `findall`/3:

```
?-setof((Departure,Destination),
   Type^flight(Departure,Destination,Type),List).


List = [(zurich,geneva),(zurich,london),(zurich,paris)];

no more solutions
```

♦

Finite failure of goal arguments

The result of a set predicate is only defined if the evaluation of its goal argument terminates. If the goal argument fails finitely, then `findall`/3 succeeds with an empty list, whereas `bagof`/3 and `setof`/3 fail altogether [Maier/Warren 89, O'Keefe 90].

The reason for this lies in the treatment of the free variables in the goal argument. If `bagof`/3 or `setof`/3 would succeed with an empty list although the goal could not be proved, subsequent goals would expect the free variables in the goal to be bound. However, because the goal failed, all variable bindings are undone, and thus no binding of a free variable can be returned.

`findall`/3 leaves unbound any free variables, and hence subsequent goals always expect a variable that is free in the goal argument of `findall`/3 to be unbound.

Declarative semantics

Set predicates have been the source of some controversy because they are a higher-order extension to first-order languages. It is not possible to give a declarative first-order semantics for `findall`/3 and `bagof`/3 since they depend heavily on the control strategy of the logic language evaluation. Because of this dependency both predicates can be used to define meta-logical predicates which cannot be defined in pure first-order logic languages, e.g. `var`/1 or negation as failure [Naish 86].

However, `setof`/3 can be given a declarative semantics because the result of the predicate is a set, and the order of set elements is independent of the order in which the individual solutions were computed [Naish 86]:

$$\texttt{setof(Template,Goal,Instantiations)} \leftrightarrow \forall\ \texttt{X}(\exists \texttt{L}_1,\ldots,\texttt{L}_n(\texttt{Goal} \wedge \texttt{X = Template}) \leftrightarrow \texttt{element(X,Instantiations)}) \wedge \texttt{sorted(Instantiations)}$$

with $\texttt{L}_1,\ldots,\texttt{L}_n$ variables in `Goal` which also occur in `Template`.

In Prolog, the set of solutions is represented as a sorted list without duplicate elements.

6.1.3 Implementation of set predicates in Prolog

The set predicates can be implemented in Prolog using `fail`/0 and the extra-logical predicates `assert`/1 and `retract`/1. The general principle is to generate a solution for `Goal`, assert it into the internal database and then fail. Backtracking will occur and another solution is computed. After having computed all answers, the asserted facts are collected into a list and removed from the database.

The following implementation of `findall`/3 is due to R. O'Keefe [O'Keefe 90]. Curly brackets {} are used to distinguish markers from solutions.

```
findall(Template,Goal,List):-
  asserta(find_all([])),          % marker for solution stack
  call(Goal),
  asserta(find_all({Template}))   % assert solution in workspace
  fail,                           % forced backtracking
  ;
  all_found([],List).             % collection of solutions

/* all_found(SoFar, List) retrieves all solutions from the workspace
  */

all_found(SoFar,List):-
  retract(find_all(Item)),
  !,
  all_found(Item,SoFar,List).

/* all_found(Item,SoFar,List) terminates if the marker [] has been
  retrieved. Otherwise Template is added to the List and retrieval
  continues */

all_found([],List,List).

all_found({Template},SoFar,List):-
  all_found([Template|SoFar],List).
```

`setof`/3 and `bagof`/3 can be implemented through `findall`/3. The goal argument is checked for existentially quantified variables. A new term `FreeVars-Template` is built from the free variables and the original template, and `findall`/3 is called with the new template term and the new goal `RealGoal`, which is obtained from `Goal` through the elimination of the ^/2 operator and arguments.

```
?- findall(FreeVars-Template, RealGoal, VarTemplatePairs).
```

The list `VarTemplatePairs` is then grouped according to the bindings of the free variables, and a list of instantiations of the template term is associated with each such variable binding. The free variables are stripped off the list `VarTemplatePairs`, and the resulting list is returned. `bagof`/3 directly returns the list together with the variable bindings of the free variables, whereas `setof`/3 sorts the list and eliminates duplicate instantiations of the template first. This is described in more detail in [Ross 89, O'Keefe 90].

Example

The sample database is

```
flight(zurich, geneva, b-737).
flight(zurich, paris, a-320).
flight(geneva, london, b-737).
```

The goal

```
?- bagof(Destination,
   Plane^flight(Departure,Destination,Plane),Destinations)
```

contains the free variable `Departure`. This goal is reformulated as

```
?- findall(Departure-Destination,
   flight(Departure,Destination,Plane),DepDestList)
```

With the database of the previous examples `DepDestList` is a list of pairs of `Departure-Destination`:

```
DepDestList = [zurich-geneva,zurich-paris,geneva-london].
```

This list is grouped according to the bindings of `Departure`. For each distinct binding of `Departure` a list containing all instantiations of `Destination` is returned:

```
Departure = zurich
Destinations = [geneva,paris];

Departure = geneva
Destinations = [london];

no more solutions
```

♦

6.1.4 Abstract implementation of set predicates

On a more abstract level the implementation of set predicates essentially consists of an evaluation part and a collection part. The evaluation part computes all solutions for a goal and saves the variable bindings of each solution. The collection part produces the list of template instantiations:

```
set_predicate_name(Template, Goal, Instantiations):-
  compute_all_solutions(Template, Goal, Bindings),
  collect_all_solutions(Template, Bindings, Instantiations).
```

This abstract definition serves to explain two important properties of set predicates:

- Set predicates cannot be implemented in pure first-order logic languages based on SLDNF resolution.
- Set predicates embed a separate all-solutions evaluation into the standard tuple-oriented evaluation of SLDNF resolution.

From the first property it follows that the evaluation mechanism underlying the set predicates can be different from that of the logic language. Set predicates can thus be seen as system predicates

whose internal implementation is irrelevant to the logic language. This is true for most commercial Prolog systems which provide set predicates as built-ins implemented in some low-level machine language for efficiency reasons.

From the second property it follows that set predicates always pertain to two distinct evaluations. For the evaluation of the current top-level goal a set predicate is simply *one next* goal to be proved. Inside a set predicate, however, a *separate* evaluation is performed which computes *all* solutions for the goal argument. Thus *all* solutions for the goal argument of the set predicate contribute to the solution of *one* goal in the main evaluation. This is expressed by `_all_` in the predicate names `compute_all_solutions` and `collect_all_solutions`.

6.1.5 Representation of set predicates

In an SLD tree set predicates can be represented as system predicate nodes. The substitutions for `Instantiations`, and, in set predicates that instantiate free variables, the substitutions for the free variables are shown as edge labels in the SLD tree. Substitutions for the template arguments and existentially quantified variables are not shown in the SLD tree.

Example

The SLD tree for the goal

```
?- Departure = zurich,
  setof((Destination,flight(Departure,Destination,Type),List),
   Type = b-737
```

is shown in Fig. 9.

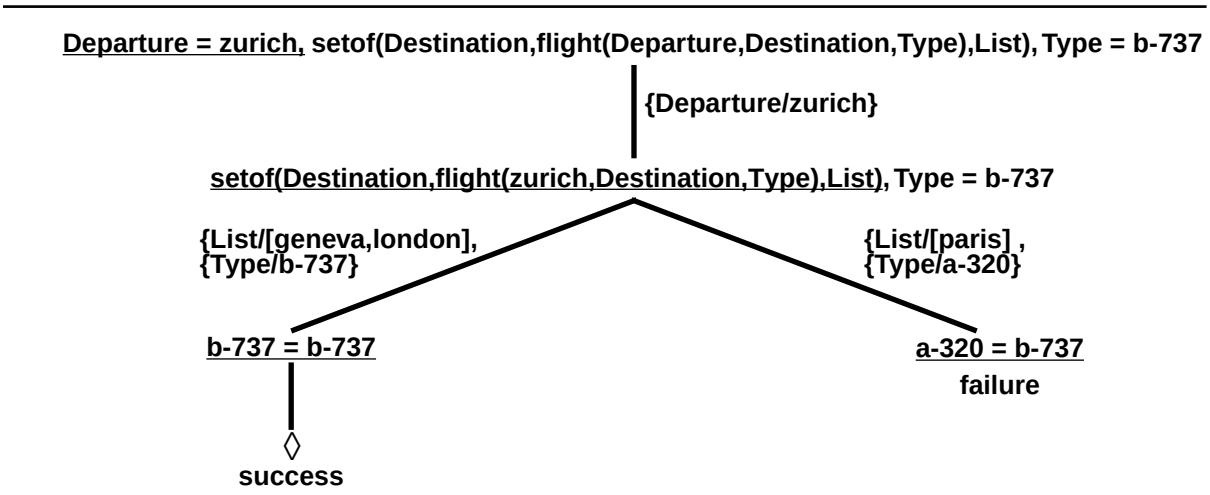


Fig. 9. SLD - tree for `setof`/3 goal

Note that the embedding of an all-solutions evaluation of the goal argument is not visible in the SLD tree.

♦

6.2 Database set predicates

Database set predicates are an extension of set predicates. Database set predicates access external database systems for the proof of their goal argument.

6.2.1 Definition

A *database set predicate* is a predicate of the form

```
db_set_predicate(ProjectionTerm,DatabaseGoal,ResultRelation).
```

where

- `db_set_predicate` is one of `db_setof` or `db_findall`.
  The prefix "`db_`" distinguishes database set predicates from the built-in set predicates (see section 6.3.6 for a discussion of the relationship between set predicates and database set predicates).
- `ProjectionTerm` is a term.
- `DatabaseGoal` is a database goal as defined in section 3.1.
  `DatabaseGoal` is the goal argument of the database set predicate, and it is evaluated in an external database system.
- `ResultRelation` is a list.
  It contains the result relation of the database evaluation of `DatabaseGoal`.

The above definition closely follows the definition of Prolog set predicates. However, it is to be seen as a generic definition only. As such it merely defines the basic arguments and the relationships that hold between them, the exact syntactical form of database set predicates depending on the language actually used.

6.2.2 Operational semantics of database set predicates

Like set predicates, database set predicates are called with the first two arguments partially instantiated terms, and the third argument an uninstantiated variable or an instantiated list.

```
db_set_predicate(+ProjectionTerm,+DatabaseGoal,?ResultRelation).
```

The basic operational semantics of database set predicates is that the database goal is evaluated in the external database system, and not by the logic language system.

The general database access procedure is as follows: when a database set predicate is encountered,

- `ProjectionTerm` and `DatabaseGoal` of the database set predicate are translated to the equivalent query in a non-procedural database language.
- The query is written into the communication channel that connects the logic language system with the database system.

- The set-oriented evaluation mechanism of the database system evaluates the query to compute the result relation.
- This result relation is written into the communication channel by the database system.
- The result relation is read in from the communication channel and placed in the logic language datastructure `ResultRelation`.

This general access procedure is shown in Fig. 10.

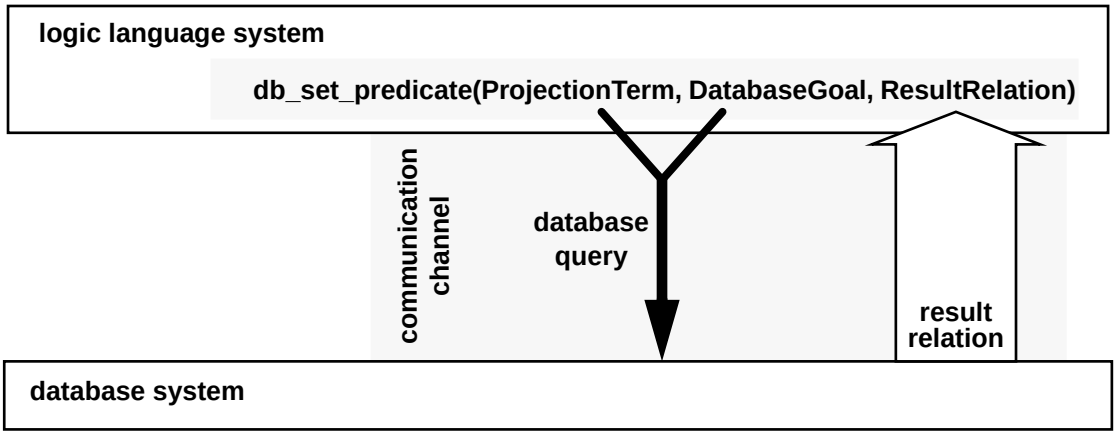


Fig. 10. Database set predicate schema

The database evaluation of the query is equivalent to an all-solutions evaluation of the database goal provided that both the translation from the logic language to the database query language and the implementation of the query evaluation mechanism in the database system are correct.

Through the translation from the logic language to the equivalent database query database set predicates implement a dynamically defined non-procedural view access to external databases. The retrieval granularity is a set-at-a-time.

6.2.3 Database access language

`ProjectionTerm` and `DatabaseGoal` together define the database access language for accessing the external database system. This database access language must be equivalent in expressive power to the query language of the database system. Restrictions on the form of both `ProjectionTerm` and `DatabaseGoal` may be necessary to match the database access language to the database query language.

`ProjectionTerm` expresses the projection on the attributes that are to be retrieved from the database system, and `DatabaseGoal` expresses the query to be evaluated by the database system. `DatabaseGoal` is formulated according to the logic language syntax and has the logic language operational semantics.

In SLDNF logic programming languages, variable arguments are bound by successful positive literals, negated literals do not return the bindings of variables, and all arguments of comparison operations and the input arguments of arithmetic functions must be bound when.the comparison or arithmetic literal is called.

Example

`flight`/4 and `plane`/2 are database predicates.

```
?- flight(No,Departure,Destination,Plane),plane(Plane,Seats),
Seats > 150.
```

is a database goal.

```
?- flight(No,Departure,Destination,Plane), plane(Plane,Seats),
X is Seats + 4, X > 150.
```

is again a database goal because the input arguments to the addition are bound, and subsequently the arguments of the comparison operation are bound.

♦

6.2.4 Implementation schema

Database set predicates are implemented according to the following schema:

```
db_set_predicate(ProjectionTerm,DatabaseGoal,ResultRelation):-
  database_goal(DatabaseGoal),
  translate(ProjectionTerm,DatabaseGoal,QueryTerm),
  evaluate_in_db(QueryTerm,DBResult),
  make_list(DBResult,ProjectionTerm,DatabaseGoal,ResultRelation).
```

In the abstract definition of set predicates of section 6.1.4 the subgoal `compute_all_solutions`/3 is implemented through `database_goal`/1, `translate`/3 and `evaluate_in_db`/2. `collect_all_solutions`/3 is implemented through `make_list`/4.

`database_goal`/1 succeeds deterministically if the goal argument of the database set predicate is a legal database goal.

`translate`/3 succeeds deterministically if its input arguments `ProjectionTerm` and `DatabaseGoal` can be translated to a database query which is represented as the term `QueryTerm` in the logic language. This translation is correct, i.e. it succeeds for legal database goals, and fails otherwise.

```
translate(ProjectionTerm,DatabaseGoal,QueryTerm):-
  translate_goal(DatabaseGoal,RelationalExpression),
  translate_template(ProjectionTerm,Projections),
  QueryTerm = query(Projections,RelationalExpression).
```

Note that there may be more than one equivalent database query for a given projection term and database goal. However, the predicate must be deterministic to prevent queries from being re-translated upon backtracking. This imposes the task of query optimization on the database system.

For efficiency reasons, `database_goal`/1 and `translate`/3 may be implemented in a single predicate.

`evaluate_in_db`/2 implements the interface to the database system. Its input argument is a term representing the database query, and its output argument is a term that captures the resulting relation. This datastructure may be partial or complete, and it may be any appropriate structured term such as a list, or a tree.

`evaluate_in_db`/2 writes the query term into the communication channel that connects the logic language system to the external database system. The query is evaluated in the database system and the result relation is sent back to `evaluate_in_db`/2 where it is placed in an appropriate datastructure.

```
evaluate_in_db(QueryTerm,ResultRelation):-
  open_communication(OutChannel,InChannel),
  send_to_db(QueryTerm,OutChannel),
  % database evaluation here - receive result relation
  read_from_db(InChannel,ResultRelation),
  close_communication(OutChannel,InChannel).
```

`make_list`/4 takes as input the projection term, the database goal, and the datastructure containing the result relation. From these it generates a list of instantiated template terms. With free variables in the database goal `make_list`/4 may be non-deterministic because for each variable binding there may exist a distinct list of instantiated template terms.

```
make_list(DBResult,Template,DatabaseGoal,ResultList):-
  free_vars(Template,DatabaseGoal,FreeVars-TemplateVars),
  group(DBResult,FreeVars-TemplateVars,ResultList).
```

The subgoals `database_goal`/1, `translate`/3, and `make_list`/4 can be implemented in a logic programming language with extra-logical predicates such as the Prolog built-ins `var`/1, `functor`/3 and `arg`/3. `evaluate_in_db`/2 refers to some evaluation mechanism outside the logic programming language, and hence it requires the ability to access this evaluation mechanism, e.g. through procedure calls or I/O to communication devices (see section 7.3 for details).

`database_goal`/1, `translate`/3, and `evaluate_in_db`/2 are all deterministic. This means that database goal and template term are translated to the database query only once, and that this query is evaluated only once.

6.2.5 Application of database set predicates

Database set predicates retrieve a set (or bag) of instantiations of the projection term from the database system and store it in a list. Generally, for the evaluation to continue, selecting elements from the set is necessary.

This selection is achieved through selection predicates. A selection predicate may be deterministic and extract only one single element from the list, or it may return one element after the other upon backtracking until the last element has been extracted, e.g. as in `element`/2

```
element([Element],Element).

element([_|Rest],Element]):-
  element(Rest,Element)
```

Database set predicates are most commonly used in a combination with a selection predicate as in

```
?- ...,
  db_set_predicate(ProjectionTerm,DatabaseGoal,ResultRelation),
  element(Element,ResultRelation),
  process(Element),
  ...
```

A combination of a database set predicate with a selection predicate can be used in any application program that accesses an external database. In such programs a call to a database predicate `p` is replaced by a combination of a database set predicate and a selection predicate. The goal argument of the database set predicate calls `p`, and the template term contains the variables which are required for the continuation of the program.

Example

In the following `flight`/4 is a database predicate.

Flight connections from `Departure` to some `Destination` are searched for. `flight`/4 is thus called with `Departure` bound and `No`, `Destination`, and `Type` uninstantiated variables.

```
?- ...,
  flight(No,Departure,Destination,Type),
  ...
```

In database set predicates the call to `flight`/4 is the goal argument.

```
?- ...,
  db_set_predicate(Next,flight(No,Departure,Next,Type),Nexts),
  element(Nexts,Destination),
  ...
```

The database set predicate is followed by the selection predicate `element`/2 which extracts from the list `Nexts` the bindings retrieved from the database for the variable `Destination`.

♦

Replacing the database goal through a database set predicate plus a selection predicate does not seem to be a particularly economic way of expressing database accesses. However, the result relation retrieved is minimal because only those attributes corresponding to variables in the projection term are retrieved, as compared to retrieving the whole relation when the database predicate is called directly.

Example

The database goal from the previous example is to be restricted. Now all flight connections with a small plane, i.e. a plane with less than 100 seats, from the current `Departure` to some `Destination` are searched for. For this a join operation of the database predicate `plane`/2 and

`flight`/4 is necessary, and a comparison operation has to be evaluated.

With direct calls to the database predicates this is formulated as follows:

```
?- ...,
  flight(No,Departure,Destination,Type),
  plane(Type,Seats),
  Seats < 100,
  ...
```

With database set predicates this can be expressed almost as easily:

```
?- ...,
  db_set_predicate(Next,
  (flight(No,Departure,Next,Type),
   plane(Type,Seats),
   Seats < 100),
  Nexts),
  element(Nexts,Destination),
  ...
```

Note that with database set predicates it is clear that the comparison operation is evaluated in the database system to reduce the number of records to retrieve.

♦

The selection predicate is not necessarily a predicate of its own. It can be integrated into the processing predicate either directly or through a sequence of folding and unfolding steps [Burstall/ Darlington 77, Tamaki/Sato 84].

Example

```
?-...
  db_set_predicate(ProjectionTerm,DatabaseGoal,ResultRelation),
  element(ResultRelation,Element),
  process(Element),
  ...
```

A new predicate `process'` is defined from `element/2` and `process`/1 by pushing the selection of an element into the heads of the predicate clauses.

```
process'([Element|_]):-
  process(Element).

process'([_|NextElement]):-
  process'(NextElement).
```

In the original goal the call to `element` and `process` is replaced by a call to `process'`:

```
?-...
  db_set_predicate(ProjectionTerm,DatabaseGoal,ResultRelation),
  process'(ResultRelation),
  ...
```

♦

6.3 Discussion

The implications of using database set predicates to access external databases in coupled systems are now discussed. On the physical level, this discussion covers the

- system architecture and the coordination of evaluations,
- memory management, and
- portability.

On the logical level, the

- restriction of the database queries and the
- applicability of higher-order control

are discussed.

Two further issues, namely the

- relationship between database set predicates and the standard set predicates and
- implementation of other database access techniques with database set predicates

are presented in the final two subsections.

6.3.1 System architecture and coordination of evaluations

Database set predicates implement a physically loosely coupled system with a client/server architecture. In this architecture, the logic language system is a client requesting services from the database system which acts as a server.

In contrast to other approaches to coupled systems which *integrate* access to the external database system into the logic language evaluation, database set predicates *embed* the set-oriented database evaluation into the tuple-oriented evaluation of a logic programming language system. Note that through embedding an external evaluation any of the existing optimizing techniques available in the existing evaluation mechanism, e.g. co-routining, can be exploited. This is of particular interest in data-intensive applications such as coupled systems.

Within their client/server architecture, database set predicates promise an efficient access to the database evaluation because

- the number of individual database accesses is reduced,
- both systems retain their proper evaluation strategies, and
- there is no interference between the database and the logic language evaluation.

These three aspects relate directly to the flow of control in database set predicates.

Representation of control flow

The flow of control within database set predicates can be described with an extended port-model. In the original model, which was developed for Prolog and which is due to Byrd [Byrd 80], a predicate is shown as a box with the four ports call, exit, redo and fail. Arrows are used to represent the flow of control in the evaluation of a predicate. The predicate is called through the call port, and if it succeeds, the exit port is used. If a subsequent goal fails, then the predicate is retried. If further solutions exist, then the exit port is used again. Otherwise the fail port is used.

This original port model is now extended to include not only the external, but also the internal control flow in predicates (Fig. 11.).

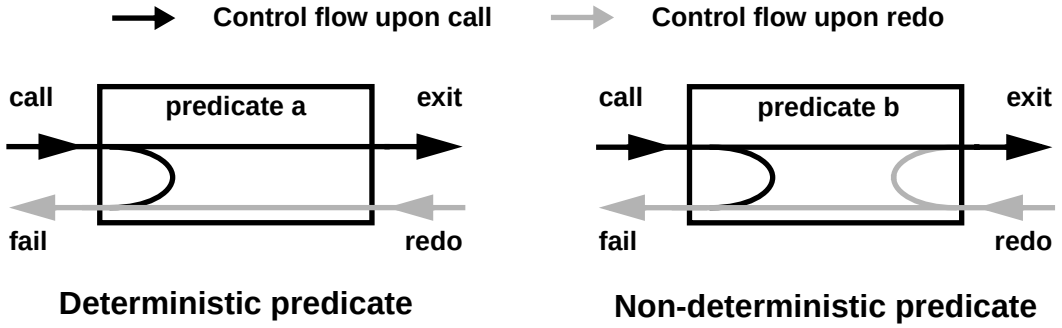


Fig. 11. Extended port model of control flow in logic language

Furthermore, the extended port model allows the explicit representation of passing control to an external evaluation mechanism through a second layer beneath the logic language (Fig. 12.).

Example

A deterministic system predicate implemented in the programming language C.

When the predicate is called, control is passed on to C. If the C evaluation is successful, then the exit port is used, otherwise the fail port.

A redo does not yield further solutions and the predicate fails directly without further access to C.

♦

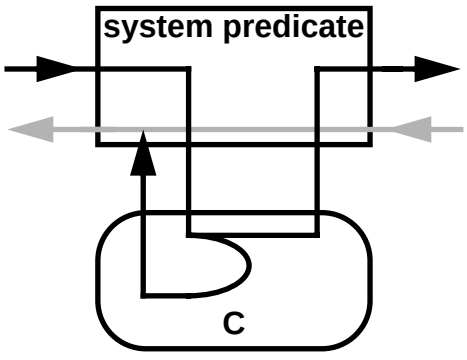


Fig. 12. Extended port model with transfer of control to external evaluation mechanism

Control flow in database set predicates

In database set predicates control is passed from the logic language system to the database system and back again. The extended port model diagram for database set predicates thus has two layers.

`db_findall`/3 always succeeds and does not yield further solutions upon redo (Fig. 13. A).

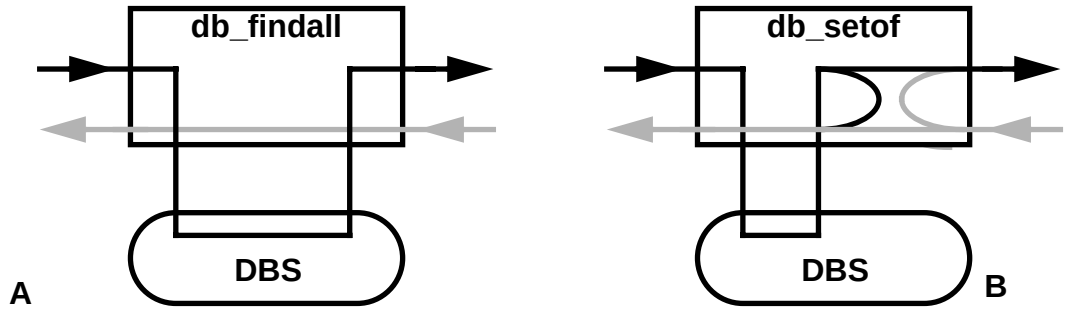


Fig. 13. Port model of the database set predicates `db_findall`/3 and `db_setof`/3

`db_setof`/3 (Fig. 13. B) fails if the database evaluation returns an empty list. Otherwise it exits with all free variables bound. Upon redo `db_setof`/3 is retried for further solutions which may only exist if the goal argument contained free variables. Because free variables are part of the database query, bindings for them have been computed by the first access to the database, and these bindings are included in the result relation that is returned from the database system. A new binding for the free variables can thus be extracted from the list representing the result relation in the logic language system. Hence, backtracking is restricted to the logic language system and no transfer of control to the database system is required when retrying `db_setof`/3.

In any database set predicate the database is accessed only once when the predicate is called, and there is no further access to the database upon redo. The database evaluation and the logic language evaluation thus are independent in the sense that there are no interferences between the two. This simple distribution of control keeps the coordination effort low.

In coupled systems in which the coordination of evaluation strategies is done through buffers or database cursors there is no such simple flow of control. In general, if the database evaluation fails, any cursor or buffer associated with the current invocation of the database predicate can be released and the predicate fails. Otherwise, the predicate succeeds with the first solution retrieved from the database system. Upon redo, the database system or the buffer is accessed again for the next solution. If another solution exists, then the predicate exits, otherwise it fails (Fig. 14.).

The decisive difference to database set predicates is that in this approach success or failure of the database predicate is determined either by the database system or the buffer manager, and thus lies outside of the logic language system. Furthermore, it requires that control passes from the logic language system to the database system or the buffer manager for every call and every redo attempt, which causes considerable administration overhead.

Control predicates

Control predicates, such as the cut `!`/1 in Prolog, are used in application programs to increase efficiency through making a predicate deterministic, or to implement some special behavior, e.g. `if-then-else`.

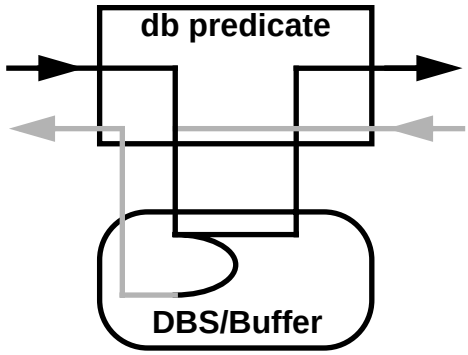


Fig. 14. Port model of database predicate with database cursor/external buffer

A control predicate affects the state of goals which have been evaluated prior to the control predicate, e.g. by removing choice points to prevent searching for alternative solutions. Thus, for control predicates to be safe, the evaluation of a database predicate must not leave choice points behind which are out of the reach of the logic language runtime system.

There are two alternative ways of handling control predicates safely: either restrict them to the logic language evaluation, or extend them to the external evaluation.

The restriction of control predicates to the logic language system can only be guaranteed if an external evaluation is deterministic, i.e. it does not leave behind choice points for alternative solutions.

In database set predicates the database evaluation computes all solutions to a query deterministically and returns them as a whole. Subsequent control predicates make the database set predicate itself deterministic, but they do not interfere with the database evaluation (Fig. 15. A). The effects of control predicates are thus restricted to the logic language evaluation.

With buffers or database cursors any redo is performed in the database system by moving the cursor, or in the buffer. When a control predicate such as `cut` is encountered after the evaluation of a database goal then either the buffer could be released or the current cursor could be dropped. However, because buffers and cursors are not part of the logic language runtime system they cannot be reached. This leads to the situation where the logic language system has cut its connection to the buffer or the cursor, but to the database system or the buffer manager these connections still exist. Subsequent calls to the database predicate will lead to associating new cursors or buffers to the predicate until no more are available (Fig. 15. B).

This problem can be remedied through an integration of the external evaluation into the logic language evaluation. This requires modifying the logic language runtime system to handle external resources such as cursors or buffers. Such an extension entails a high implementation effort and furthermore severely restricts the portability of a coupled system because such a modification is highly dependent on low-level implementation or operating system details.

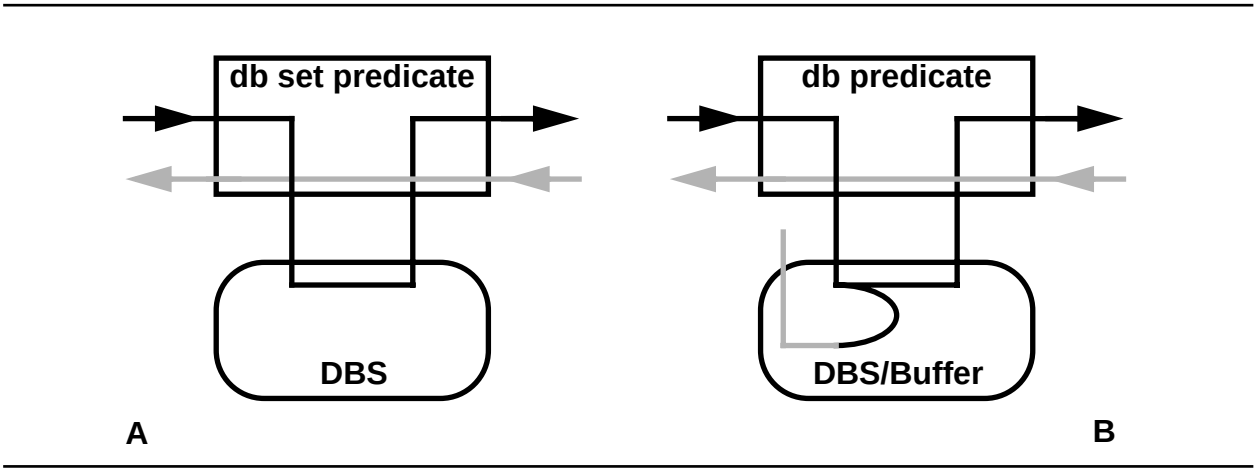


Fig. 15. Effect of control predicate `cut`

6.3.2 Memory requirements

In coupled systems the amount of data stored in external databases by far exceeds the size of main memory available to the logic language system. Techniques thus have to be developed to access this data efficiently without causing memory overflow.

Memory demand can be subdivided into static demand, which is the amount of memory cells allocated for a datastructure in the logic language implementation, and dynamic demand, which is determined by the actual datastructure instances created during an evaluation at run-time. Static memory demand is system dependent, whereas dynamic demand depends on the application program.

Static memory demand is determined by the

- database retrieval granularity, the
- datastructures used to hold the data retrieved, and the
- memory management in the logic language system.

Retrieval granularity

The granularity of data retrieval in coupled systems is either a single record at-a-time or set- or relation-at-a-time.

Record retrieval matches the tuple-oriented evaluation strategy of the logic language system. In general, however, more than one record has to be retrieved until a matching record is found. This requires the repeated execution of a fetch-next-record operation, which means that either the database system or a buffer is accessed repeatedly. Because of the administration and communication overhead involved, retrieving all the records one by one from a relation is slower than retrieving the relation as a whole. This is especially true if the record has to be transferred to the logic language system before it can be determined whether it matches the original goal.

With set retrieval part of or an entire relation is retrieved from the database system. Set retrieval reduces or even eliminates the need for coordination mechanisms, but in general more data is retrieved from the database system than is necessary for the evaluation to continue. Especially in recursive programs this may lead to memory overflow.

Despite this problem, set retrieval is justified if queries can be restricted to yield small result relations, or if all solutions are to be computed. There is no alternative to set retrieval if the result relation as a whole is of interest.

Datastructures

The basic datastructure in logic language systems is the term. A term is either a constant, a variable, or an n-ary function symbol with n arguments which may be terms themselves. Lists are 2-ary terms with the functor '.', the first argument being a term which represents a list item, the second argument a list. Program clauses are binary terms with the functor ':-' and the first argument the head of the clause, the second argument the clause body.

Constants, variables, and functors all require at least one memory cell for their representation in the system. An n-ary term with atomic arguments requires a minimum of `n+1` memory cells, one for the functor, and n for the arguments (Fig. 16.).

n-ary structured term `p(a,b,X)` requires `n+1` memory cells

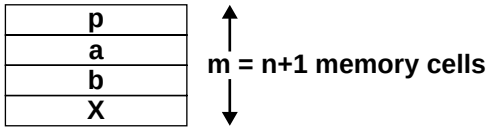


Fig. 16. Structured term memory requirements

Because lists are so common in logic programs, a space efficient representation has been implemented in most systems. In this representation, the list functor '.' is omitted. A list with `n` elements which are terms of size `m` thus requires `n(m+2)` memory cells (Fig. 17.).

List representation of list with `n` elements each of size `m` requires `n(m+2)` cells

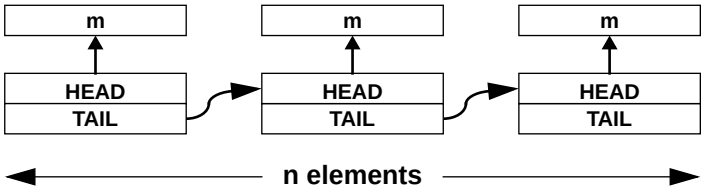


Fig. 17. List datastructure memory requirements

More space-efficient representations of lists have been developed which cluster list elements [Dobry 90]. With these list representations the space requirements may be reduced to `n*m+1` cells.

The naive representation of a clause requires space for the head, for the body, plus at least three memory cells, one for the head, one for the body, and one for the next clause to follow the current

clause. n facts of size m thus require a minimum of `n(m+3)` cells. More sophisticated representations, which trade space efficiency for indexed access, require additional space for the index.

Database set predicates store the result relation of a database evaluation in a list. Each item in the list corresponds to a row in the result relation. Hence, the space requirements of database set predicates are `n(m+2)`. To reduce memory demand, the clustering technique for the representation of lists may well be used because the result relation is retrieved as a whole.

In advanced Prolog implementations – such as SEPIA-Prolog [Meier et al. 89] – which feature arrays, a result relation can be stored efficiently in an array. The space requirements are similar to those of the clustering technique, and each element may be accessed in linear time through its position in the array.

The alternative to using lists or other dynamic datastructures is to assert the relation into the workspace of the logic language system. However, this requires at least `n(m+3)` cells, plus considerable space allocation for the index.

Memory management

For the actual evaluation of a program not only the space requirements of datastructures, but also the time efficiency of their manipulation is relevant.

Memory in currently implemented logic language systems is divided into two major areas, *code space* and *data space* [Warren 83, Dobry 90].

The code space holds the program clauses and a symbol table which serves as a system dictionary. The contents of the code space are rather static, so that expensive retrieval optimizations such as indexing techniques may be implemented. A program is assumed not to change during its evaluation. Under this assumption, the program code requires a constant amount of memory in the code space, and the gain in efficiency through indexed access outweighs by far the considerable administration effort and additional space requirements.

The code space can be modified through program modification commands such as `assert`/1 or `retract`/1. This manipulation of the code space is very time-consuming (approx. 20 times slower than a lookup in the code space in Quintus Prolog 3.0) because extensive re-indexing is required after each update. Furthermore, the effects of `assert`/1 and `retract`/1 are not undone upon backtracking so that any de-allocation of memory must be programmed explicitly.

The data space stores dynamic datastructures created during the evaluation of a program. In the data space, a memory manager is responsible for an efficient allocation and de-allocation of memory during the evaluation of a goal. In general, memory is allocated when a clause is called, and it is de-allocated when a clause fails. Control predicates may lead to memory being de-allocated early and thus contribute to reduce demand for memory. In addition to that garbage collection may be applied to reclaim memory for datastructures which are no longer needed in the current evaluation.

With database set predicates the result relation retrieved from the external database is stored as a dynamic datastructure in the data space of the logic language system. The built-in memory manager thus can be exploited to reduce space demand and increase time efficiency. Furthermore, memory is allocated and de-allocated implicitly, and it is guaranteed that memory is only allocated as long as it is needed in the current evaluation.

6.3.3 Portability

An approach to coupled systems is said to be *portable* if it can be implemented on a variety of machines, under various operating systems, and for different logic languages and database systems.

Portability is determined by the specific system resources that are required. A coupled system is thus portable if its implementation requires only such resources which are already provided as standard features in both the logic language system or the database system.

In coupled systems portability is achieved by

- restricting the exchange of data between the logic language system and the database system to high-level standard interfaces.

Any modification of the runtime system of the logic language, the use of auxiliary interfaces, or low-level database access, prevents a system from being easily portable.

The system resources required by database set predicates are an interface to a communication device of the operating system from both the logic language system and the database system. Currently available logic language systems in general provide such an interface via built-in predicates which allow reading from and writing to files or streams. Commercial database systems also provide similar interfaces either for direct user access or for programming languages.

Database set predicates access external databases in a non-procedural manner through queries formulated in a high-level query language. A query is generated from the goal argument of a database set predicate in a translation procedure. This translation procedure can be implemented *entirely* in the logic language itself without any need to resort other languages. Furthermore, because a database goal is translated *directly* to an equivalent query there are no intermediate translations to be performed as is the case with a distinct module interface as in PRIMO. Finally, a high-level programming language such as a logic language greatly facilitates the implementation of a translation procedure. Thus, adapting a given translation procedure to different database languages, extending it to include new features, or porting it to another machine is straightforward (see section 7.2 for details of the translation procedure).

Embedding an external database evaluation into the logic language evaluation requires adequate datastructures to capture the data retrieved from the external database. In database set predicates, data retrieved from the external database is interpreted and placed in a list of terms, the arguments of which are ground values. This interpretation is done by the logic language system, and it can be

implemented entirely in the logic language, or the built-in tokenizer, which is provided to parse user input, may be used.

In systems using buffers or database cursors, managing these external resources requires major modifications of the logic language runtime system. Because a runtime system is in general written in low-level languages and not accessible to programmers, incorporating these modifications is difficult.

6.3.4 Restriction of queries

In coupled systems a subset or an extension of the logic language is used to access the external database system. In database set predicates the database access language is a subset of the logic language. Maximally restrictive queries can be formulated which minimize the amount of data retrieved from the database system. This reduces the cost of transport, may prevent memory overflow and thus increases efficiency.

In logic languages, various techniques can be employed to achieve maximally restrictive queries:

- propagating variable bindings into the queries,
- exploiting join selectivity,
- dynamic database access definition, and
- independent selection and projection expressions.

The first two have been used in other approaches to coupled systems already and thus will only be sketched. Dynamic database access definition is new only in physically loosely coupled systems, whereas independent selection and projection expressions are new in the context of coupled systems in general.

Database set predicates allow all four techniques to be employed to effectively restrict queries as strong as possible. The word of warning of section 6.3.2 that set retrieval is only justified if result relations are small directly relates to this section. It will be shown that in fact result relations retrieved through database set predicates are minimal and that database set predicates are thus an efficient means of implementing coupled systems.

Propagating variable bindings into queries

The arguments of database goals are constants and variables, or terms containing constants and variables. Each argument is mapped to an attribute in a database table. In the query corresponding to the database goal unbound variable arguments are mapped to attribute names and variable arguments bound to constants are mapped to comparison operations with the appropriate attribute name as one argument, and the constant value as the second argument. This comparison operation serves as a selection condition to restrict the query.

Example

The database goal

```
?- ...,flight(FlightNo,Departure,Destination,Plane).
```

with `Departure` bound to the constant value `zurich` is equivalent to the relational algebra expression

$\sigma_{\texttt{FLIGHT.Departure=zurich}}(\texttt{FLIGHT})$

♦

The propagation of variable bindings into database queries allows queries to be restricted dynamically at runtime and thus serve to restrict the amount of data to be retrieved to those tuples which are really needed for the evaluation to continue.

Propagating variable bindings is only possible if the language used for database access and the logic language have common constructs through which the variable bindings can be exchanged. In PROSQL SQL commands are treated as atoms whose internal structure is not accessible through the Prolog system. The database access language and the logic language are completely separated, and thus propagation of bindings is not feasible in PROSQL. The same is true for KB-Prolog where the relational algebra expressions may not contain variables. In most other systems propagation of bindings is provided.

In database set predicates the propagation of variable bindings is achieved during the translation of the template term and the database goal.

Exploiting join selectivity

The most commonly used form of a join is the natural join which implies an equality comparison over at least one attribute from both argument relations as the join condition. Join operations can be used to restrict queries because the comparison operation also serves as a selection condition for the two relations.

Join operations require at least two relations as input arguments. Self-joins, which are joins over only one relation table, are only a special case of the general join. In coupled systems joins can be performed in the logic language system or in the database system. It is very expensive to perform joins in the logic language system because both relations involved have to be retrieved from the database system prior to the evaluation of the join. Performing joins in the database is much more efficient because database systems support join operations through e.g. indexed access to records, and because only the result relation need be retrieved.

In coupled systems with single relation access to the database joins can only be performed in the logic language system. For joins to be performed in the database view access to the database is necessary.

In the logic language natural join is expressed through shared variables in the individual subgoals of a database goal. More general join operations are expressed through comparison operations over two variables from distinct subgoals.

Example

The database goal

```
?- flight(FlightNo,zurich,Destination,Type), plane(Type,Seats).
```

is equivalent to the following natural join

```
FLIGHT [FLIGHT.Plane = PLANE.Type] PLANE
```

The database goal

```
?-flight(FlightNo,Departure,Destination,Type_1),
  plane(Type_2, Seats),
  Type_1 < Type_2.
```

is equivalent to the following join with < comparison over the attribute `PlaneTypes`.

```
FLIGHT [FLIGHT.Plane < PLANE.Type] PLANE
```

With single relation access both relations `FLIGHT` and `PLANE` have to be retrieved from the database system for the evaluation of the join. With view access the join is evaluated in the database system, and only the result relation is retrieved.

♦

Note that exploiting join-selectivity is not restricted to two relations. On the contrary, with more relations involved the selectivity potential of a join improves.

In database set predicates join selectivity can be fully exploited because the database goal may consist of an arbitrary number of conjunctive or disjunctive database subgoals. Database goals with disjunction are split into as large as possible base conjunctions connected through disjunction via transformations according to de Morgan’s laws.

In coupled systems, such as CGW or BERMUDA, where database access is restricted to single relation access, join selectivity cannot be exploited. In PRIMO joins are evaluated in the database system, but the relations involved are asserted into the workspace as distinct relations. Therefore any join must be performed twice - once in the database system, and again in the logic language system.

Dynamic database access definition

In physically loosely coupled systems access to the database is either defined

- statically as part of the program code, or
- dynamically through datastructures.

With static database access definition database predicates are program clauses. These clauses are mapped to query skeletons which may be instantiated with current variable bindings. This mapping

is usually done at compile-time, as in commercial Prologs, the system by Danielsson, BERMUDA, Educe, CGW and PRIMO. The propagation of variable bindings into the query is done at runtime.

Example

The following program excerpt written in Quintus Prolog

```
:- db_name(flight,unify,'~unify/...').

db(flight,example,flight(
  'FLIGHTNO':string,
  'DEPARTURE':string,
  'DESTINATION':string,
  'TYPE':string)).

:- db_connect(flight).
```

statically defines the database predicate `flight`/4 as part of the program code. The corresponding relation table is accessible via the database management system Unify™.

♦

Systems with delayed evaluation, such as the system by Demolombe or the one by Nussbaum, collect individual database access requests and formulate complex queries at runtime. They thus rely on dynamic query definition. However, both these systems are physically tightly coupled systems.

With database set predicates dynamic query formulation is feasible in physically loosely coupled systems too. In database set predicates access to the database is defined through terms which are passed on to the predicate as arguments. Terms are standard datastructures which can be constructed at runtime without side-effects.

Example

The following goal retrieves all cities that can be reached by big planes from `zurich`.

```
?- ...,
  DatabaseGoal =
   FlightNo^Type^Seats^
    (flight(FlightNo,zurich,City,Type),
    plane(Type,Seats),
    Seats > 150),

  db_setof(City,DatabaseGoal,List),...
```

The call to the database set predicate retrieves all bindings for `City` and collects them in `List`.

♦

The main advantage of dynamic database access definition is that more information from the current state of the evaluation can be conveyed to the database system than with static database access. Furthermore, with static database access it is necessary that each different query requires a

separate definition. With database set predicates the actual database access is determined by the arguments to the database set predicate, and thus queries are formulated without explicit definition.

Independence of selection and projection expressions

In coupled systems selection is expressed through explicit comparison operations or implicitly via variable bindings in the logic language. Projection can be expressed in a variety of ways: either through a reserved variable identifier, by defining a database predicate as a rule, through projection operators, or by using a projection term.

In Prolog a limited form of projection is expressed through the anonymous variable "_". The anonymous variable may be used to mask specific arguments which are of no interest.

Example

The following goal

```
?- flight(_,zurich, Destination, Type)
```

expresses projection on the attributes corresponding to the second, third, and fourth argument position in relation `FLIGHT`.

♦

However, for join operations a variable must be given a name, and this automatically leads to the binding for the variable being returned, even if this binding is of no interest.

Projection can also be expressed through rules. This technique (or a variation thereof) is used in Educe, CGW, PRIMO, BERMUDA, and most commercial Prologs.

```
retrieve(ProjArg1,...,ProjArgn):-
  <body of rule during the evaluation of which ProjArgi are bound>
```

expresses projection on the attributes corresponding to the arguments in the head of the rule. The problem with this technique is that attributes for which there is no argument in the head of the rule cannot be accessed from goals calling the rule.

Example

```
retrieve(Destination,Type):-
  flight(FlightNo,Departure,Destination,Type).
```

The attributes `FlightNo` and `Departure` are invisible to any calling goal, and hence cannot be used to express selection conditions.

♦

Projection operators, such as `:^:` in KB-Prolog, directly express projection on the specified attributes.

Example

```
tmprel isr [destination, plane] :^: flight
```

creates a relation named `tmprel` from the attributes `destination` and `plane` in KB-Prolog.

♦

The major disadvantage of projection operators is that they are defined statically as part of the program code, and that they rely on side-effects.

In database set predicates projection is expressed through a projection term. Its arguments correspond to the projection attributes in a query. A projection terms is used in conjunction with a database goal, and the connection between the two is established through common variables.

```
?- db_set_predicate((ProjArg1,...,ProjArgn),(ProjArgi,OtherArgj),...)
```

With a projection term it is possible to express projection independently of the other database operations which constitute the query. All variables of the database goal are thus accessible, and thus any binding of a variable occurring in the database goal is exploited to restrict the query evaluation.

Example

```
?- ...,
  db_setof((Destination,Type),
  (flight(FlightNo,Departure,Destination,Type),
   plane(Type,Seats),
   Seats < 150),
  List),...
```

retrieves all instances of the projection term `(Destination,Type)` from the result relation of the selection `Seats < 150` and the natural join over the attribute `PlaneType` in `FLIGHT` and `PLANE`. With `FlightNo` and `Departure` bound to a constant value the query is restricted even further.

♦

Furthermore, with projection terms it is possible to arrange attributes retrieved from the database in a particular order, e.g. to express groupings of attribute values.

6.3.5 Higher-order control

The term *higher-order* is used in the sense that set predicates in general, and database set predicates in particular, allow reasoning about a *collection* of solutions to a goal. Higher-order control thus allows statements to be made about the evaluation of a goal as a whole, which is not expressible in the object language. Typical higher-order operations are grouping and sorting, and higher-order functions include aggregate functions which compute values over sets of attributes.

Higher-order control is useful in at least two respects:

- "good" solutions can be found early through reordering and the elimination of duplicate solutions, and
- sets of solutions can be compared with each other through aggregate functions.

For efficiency reasons as much higher-order control as possible should be delegated to the database system. This requires that

- the database access language be able to adequately express higher-order constructs, and that
- the database system provide the appropriate operations.

Although higher-order operations are not part of the relational database model most commercial database managements systems support sorting, grouping of result relations and aggregate functions over relations.

Grouping, sorting, and elimination of duplicate solutions

In database set predicates grouping is expressed either through free variables in the database goal or through an extension of the projection term.

With free variables used to express grouping, for each binding of the free variables a set of solutions is returned. Thus, free variables represent the grouping attributes, whereas the other variables represent grouped attributes. Note that expressing grouping through free variables is only possible with `db_setof`/3, because the bindings of its free variables are returned.

The projection term can also be used to express grouping if the result relation is sorted according to the arguments of the projection term. For this the projection term may itself be a structured term.

Example

```
db_setof((Type,(Departure,Destination)),
  FlightNo^flight(FlightNo,Departure,Destination,Type),List).
```

returns the whole result relation at once, grouped according to the argument variable `Type`

```
List = [
  (a-320,(zurich,paris)),
  (b-737,(zurich,geneva)),
  (b-737,(geneva,london))];

no more solutions
```

♦

Sorting and the elimination of duplicate solutions is expressed implicitly through the use of `db_setof`/3. The result relation is sorted in ascending order by the free variables, if any, in the database goal, and the arguments in the projection term. Because the projection term can be constructed at runtime the ordering of solutions can be specified dynamically through changing the order of arguments.

Aggregate functions

Aggregate functions compute values over collections — or aggregates — of attribute values. Typical aggregate functions are `sum`(), `avg`(), `count`(), `min`(), and `max`() which compute the sum, the average, the number, the minimum and the maximum of given attributes.

In database set predicates calls to aggregate functions are ternary subgoals in the database goal. The predicate symbol of such a subgoal is mapped to the function name in the database system. The first argument of the subgoal is mapped to the attribute over which the function is to be computed, the second argument specifies the relation, and the third argument receives the result value of the function evaluation. Because this value is of interest the variable in the result position of the aggregate function subgoal must also occur in the projection term.

Example

"Find the smallest plane in the database"

```
db_setof(MinSeats,
  min(Seats,Plane^plane(Plane,Seats),MinSeats),List).
```

returns

```
List = [150];

no more solutions
```

`MinSeats`, which is the function value of interest, occurs in the database goal as the result argument of the aggregate function subgoal `min`/3, and in the projection term.

With `Plane` a free variable, the result of the function would be grouped by the corresponding attribute values. For the aggregate function to be computed over the whole relation, `Plane` must be existentially quantified.

♦

In some database languages, e.g. QUEL [Held et al. 75], aggregate functions may have complex input argument arguments, e.g. arithmetic expressions over attributes, or they may even be nested. Such complex or nested aggregate functions can also be represented in the logic language and hence also in database set predicates.

6.3.6 Relationship between the built-in set predicates and database set predicates

The main difference between the built-in and database set predicates lies in the constraints on the goal argument:

- the extension of a predicate called in the goal argument must be stored either externally, or internally only, and
- the goal argument may contain calls to either database predicates or program predicates only.

Under these two constraints, database set predicates can be used in parallel to the built-in set predicates of logic languages.

This can be achieved by a mutually exclusive test in the clauses defining the set predicates. This test serves to select the appropriate set predicate definition. A suitable test is whether the goal argument is in fact a valid database goal. If so, then the goal argument can be proved from database predicates in an external database evaluation. Otherwise it must be proved from program predicates.

Example

`findall`/3 is redefined as follows (with the database set predicate `db_findall`/3 renamed to `findall`/3):

```
findall(Template, Goal, List):-
  not database_goal(Goal),
  /* built-in implementation of findall */
  ...

findall(Template, Database_Goal, List):-
  database_goal(Database_Goal),
  /* database set predicate implementation */
  ...
```

The first clause of `findall`/3 succeeds if the goal can be proved from the clauses stored in the internal workspace. The second clause succeeds if the goal can be proved using facts stored in the external database system. Either clause returns an empty list if the goal argument could not be proved.

♦

If set predicates and database set predicates are used in parallel in a program the physical allocation of data accessed through these predicates must not be known to the programmer. With the database schema information accessible through the program it is thus possible to build a prototype that accesses only the internal workspace, and then, in the final version, relocate the database to an external database system without changing the program.

6.3.7 Implementation of other approaches with database set predicates

In the introduction it was claimed that database set predicates can simulate most other techniques developed so far for the coordination of evaluation strategies in coupled systems. This is shown by example for asserting result relations into workspace, and for single tuple retrieval. Both these approaches rely on the constraint that data is stored either externally or internally, but not both. With the subsumption technique this assumption could be dropped — the extension of a database predicate is stored externally, but part of it is also held internally for efficient access.

Asserting relations

Asserting relations into the workspace can be represented with database set predicates through retrieving the set of solutions of a database predicate, and asserting, one by one, each instantiated tuple.

```
retrieve_and_assert(DatabaseGoal):-
  db_set_predicate(DatabaseGoal,DatabaseGoal,RelationList),
  assert_all(RelationList).

assert_all([]).

assert_all([Head|Tail]):-
  asserta(Head),
  assert_all(Tail).
```

Redundant clauses can be avoided through an additional check before asserting a clause into the workspace. The second clause of `assert_all`/1 is modified accordingly. Note that the check consists of a meta-variable which is instantiated with a goal.

```
assert_all([Head|Tail]):-
  /* check that clause Head does not already exist in workspace */
   call(Head) -> true,!
  ;
   asserta(Head),
  assert_all(Tail).
```

Asserting relations into the workspace is best employed once in an application program prior to any access to the data stored externally.

Single tuple interface

A single-tuple interface to the database system can be implemented with database set predicates in the following way: a new clause with an appropriately chosen name is added to the program. The head of the clause contains an argument for each attribute to be retrieved from the database. The body of the clause contains a call of a database set predicate with the arguments of the head as the template and a database goal that contains at least these arguments. The selection predicate `element`/2 returns one tuple at a time from the result relation upon backtracking.

```
retrieve_tuple(Arg1,…,Argn):-
  db_set_pred((Arg1,…,Argn),db_goal(Arg1,…,Argn),ResultRelation),
  element(RelationList,(Arg1,...,Argn)).
```

Note that this definition can be modified to yield a very general single tuple database interface by replacing the n arguments in the head through only one argument which may be a term representing a goal. This term is also used as the projection term and the database goal of the database set predicate, and it is used as the selection mask in `element`/2:

```
retrieve_tuple(Goal):-
  db_set_pred(Goal,Goal,ResultRelation),
  element(ResultRelation,Goal,).
```

With this definition, any term representing a database request can be executed in the logic program. Note that this definition makes use of the fact that the template variables and the existentially quantified variables in the database goal remain unbound after the execution of the database set predicate.

Subsumption

The subsumption technique was primarily developed to replace the number of expensive individual accesses to external databases through cheap lookup in the internal workspace. Upon the first occurrence of a database goal its extension is loaded into workspace, so that for further requests it can be accessed efficiently. Query subsumption is used to test whether data has to be fetched from the database system, or is simply searched for in the logic language workspace.

Query subsumption requires tracer predicates that record which queries have been evaluated in the database already. With database set predicates query subsumption can be implemented according to the following definition:

```
subsumption_access(Goal):-
  tracer(Goal,Tracer),
  subsumes(Tracer,Goal), % Goal extension is in workspace already
  !, % to prevent second clause from being tried
  call(Goal).

subsumption_access(Goal):-
  % Goal not yet answered by database evaluation
  db_set_pred(Goal,Goal,List),
  % permanently store tuples retrieved from db
  assert_all(List),
  % update tracer record
  modify_tracer(Goal),
  call(Goal).
```

Note that the second clause of `subsumption_access`/2 relies on the immediate update of the internal workspace. As in the original model proposed by [Ceri et al. 87] the tracers are updated through `modify_tracer`/1. Tracers are asserted in front of each other so that the tracers for every query are organized as a stack. Care must be taken to prevent backtracking into the second clause of `subsumption_access`/1 to prevent the modification of tracers other than the current tracer.

6.4 Summary

With database set predicates both the logic language system and the external database system are completely independent, communicating with each other only upon request from the application program written in the logic language. Database access is defined dynamically, and the database access language is a subset of the logic language. Database set predicates thus implement a true physically loosely and logically tightly coupled system (Fig. 18.).

On the physical level efficiency is achieved through a simple flow of control that does not cause coordination overhead, efficient datastructures, and automatic memory management by the logic language system. On the logical level efficiency is achieved through maximally restrictive queries. Set retrieval, which is a source of inefficiency in other approaches because of the expensive storage of result relations, contributes to efficiency in database set predicates because it minimizes the number of individual database accesses, and allows the application of higher-order control to the current evaluation.

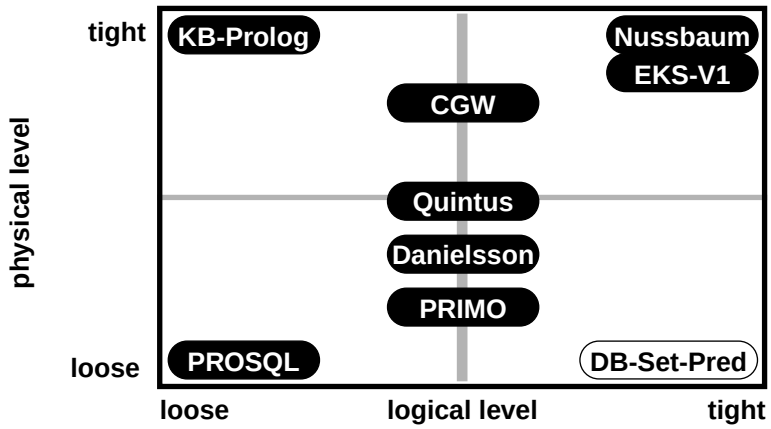


Fig. 18. Matrix positions of coupled system approaches

The implementation effort for database set predicates is low. Database set predicates can be implemented entirely in a high-level logic programming language. The efficiency of such an implementation is fully sufficient because today's logic programming language systems, such as commercially available Prolog systems, are fast. Translating a database goal to the equivalent query is an inexpensive operation. Also, the interpretation of the data retrieved from the external database system can be coded efficiently in logic programming languages.

The independence of database set predicates of a particular database management system to connect to is high. Only standard interfaces are used: the query interface of the database system, and an operating system interface, such as streams, in the logic language system. There is no need for low-level coordination between the two systems. The direct translation from the logic language to a database language allows accessing a variety of database systems via a non-procedural database access language. For each database language a compiler must be provided. However, this is not a severe restriction because such compilers are easily written, and some are available already in the public domain.

The expressive power of database set predicates is determined by the expressive power of the database access language. With relational databases, it is restricted to relational algebra, i.e. atomic attributes and recursion-free. Higher database access languages are allowed, and higher-order control can be expressed, if they are supported by the external database system. Thus, an increase in the expressive power of underlying database language is directly available to the database access language with database set predicates, the only restriction being that the database access language is a sublanguage of a first-order predicate logic language.

Naturalness is high with database set predicates because there is only one language to be used in an application program. Database access is visible through the reserved names of database set predicates. Changing the physical allocation of data from the internal workspace to external databases does not necessarily entail changing the application program, especially if the database schema information can be retrieved dynamically from the external database. Furthermore,

because the data retrieval behavior of most other approaches to coupled systems can be simulated with database set predicates with little, if any, loss of efficiency, database set predicates are a very flexible and powerful means of accessing external databases.

The values for the characteristic criteria of coupled systems are displayed in Fig. 19.

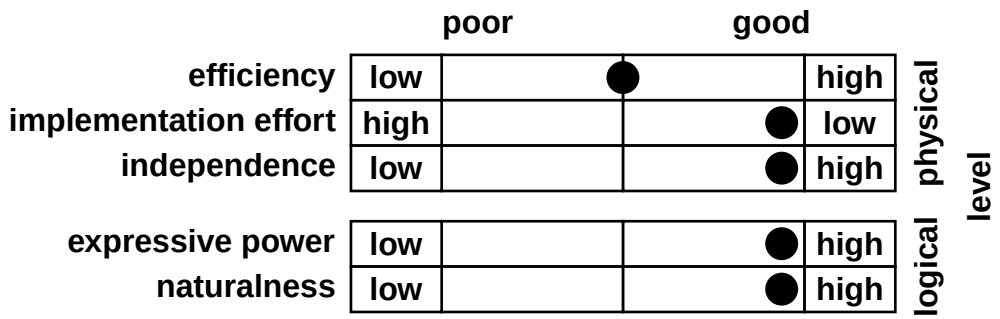


Fig. 19. Values for qualitative criteria of database set predicates

Note that compared with the values for physically loosely coupled systems of Fig. 6. on page 43, efficiency is considerably better in database set predicates. This is due to the database access language allowing more restrictive queries than in other approaches, and it is due to using an efficient dynamic datastructure to hold result relations.

Restrictions

The major restriction of database set predicates is that memory overflow can occur through unrestricted queries over large relations. This danger is real in recursive programs, such as path-finding algorithms, where a large part of a relation may be read in in every recursion step. Note that this problem is not restricted to database set predicates, but pertains to all systems with set retrieval (and, to a lesser degree, even to systems with tuple-at-a-time retrieval granularity).

The most promising remedy of this problem is to maximally restrict queries, and this has been shown to be possible with database set predicates.

Part III

Implementation

7

Implementation of Database Set Predicates

In the remainder of the thesis the logic programming language will be Prolog and the database system is an SQL system. Prolog has been chosen because it is the most widespread logic programming language implementation, and SQL because it is the current relational database language standard.

7.1 System architecture and requirements for database set predicates

Database set predicates can be implemented efficiently in existing Prolog systems provided that either calls to externally defined procedures are supported, or accessing operating system communication devices is allowed. Most commercial Prolog system implementations provide one of the above mechanisms. The database system must also feature a programming language interface, or an interface to the communication devices of the operating system. Again, most commercially available database systems feature such an interface.

7.1.1 System architecture

Database set predicates implement a physically loosely and logically tightly coupled system in which access to the external database is embedded into the logic language. The general architecture of a coupled system based on database set predicates is a programming language system connected to an external database system through a bi-directional communication channel (Fig. 10. on page 71).

In this architecture the Prolog system is simply another user to the database management system. An application program must have the access privileges for each relation table and view that it accesses, and it must register with the database system through a login procedure. This login procedure can be executed when the application program is loaded into the Prolog system, when the communication channel to the external database is established, or prior to the first database access request.

7.1.2 Database set predicates implementation requirements

The implementation of database set predicates requires that a

- database access request be translated to the equivalent SQL query, and that the
- result of the database evaluation be retrieved and placed in a Prolog list datastructure.

Translating the database access request and the result relation retrieved from the database system can be implemented in standard Prolog. In fact, logic languages are well-suited for the implementation of interpreters and compilers [Warren 80, Sterling/Shapiro 86].

This translation of a database access request to the database query requires meta-level access to the object language, and it entails extensive term manipulation. The meta-logical predicates such as `var`/1, `functor`/3, `arg`/3, or `=..`/2 test whether a token of the database access request is a variable, extract the functor or an argument of a term, or transform a term into a list respectively. Furthermore, in order to allow the assignment of unique identifiers to tokens, a generator of symbols, e.g. the built-in predicate `gensym`/2, is needed.

For the connection to the database system there are two possibilities: communication through procedure calls, or inter-process communication. Communication via procedure calls is possible only in Prolog systems which allow predicates to be defined externally as procedures in a procedural programming language and provide a calling mechanism to such procedures. Inter-process communication requires access to operating system communication devices such as streams or pipes.

The retrieval of data from the database system, and the construction of a list to capture the result relation depends to a large extent on the type of communication between the two systems. With communication through procedure calls high-level Prolog datastructures can be exchanged with the database system as procedure arguments, and therefore only standard term manipulation is needed. With inter-process communication, data exchange is possible only on the basis of single characters, and hence low-level I/O predicates such as `get`/1 and `put`/1 must be used to read in or write out single characters, and extra-logical predicates such as `name`/2 to construct terms from sequences of characters.

7.2 Translation from Prolog to SQL

`ProjectionTerm` and `DatabaseGoal` are translated to an equivalent SQL query. This translation is based on the

- schema information of the database to be accessed, and a
- translation procedure for the database access request.

The database schema information is application dependent. For each database accessed schema information must be available. The translation procedure is independent of an application program, but dependent on the database access language in the logic language and the target database query language.

The translation from Prolog to SQL has been described in the literature already [Jarke et al. 84, Marti et al. 89, Danielsson/Barklund 90]. My presentation is thus only an overview. However, it must be noted that the translation of higher-order control constructs such as grouping and sorting, and the translation of arithmetic expressions has — to my knowledge — not been described previously.

7.2.1 Representation of schema information

Schema information is the information about the relations and attributes of external relational databases. This schema information must be accessible by the translation program for the mapping of predicates in the database goal to the appropriate database relations. It can be provided either statically or dynamically. In the first case the database schema information is included as facts in the Prolog program code. In the second case this information is automatically retrieved from the database administration tables in the database system prior to any database access.

The basic problem to overcome in the translation from Prolog to SQL is the different addressing of arguments and attributes respectively. In Prolog arguments are identified through their position in terms, whereas in SQL attributes are identified through their names and relations. Thus, the mapping of Prolog terms to SQL relations is a mapping of argument positions to qualified attribute names.

In the compiler presented here the database schema information is represented through Prolog facts. This representation is provided at compile time already. It is thus static.

Example

For the sample application of section 5.1 the database schema information is stored as follows:

```
% relation(PredicateName,RelationName,Arity)

relation(flight,'FLIGHT',4).
relation(plane,'PLANE',2).

% attribute(AttributeName,RelationName,Position)

attribute('FLIGHT_NO','FLIGHT',1).
attribute('DEPARTURE','FLIGHT',2).
attribute('DESTINATION','FLIGHT',3).
attribute('TYPE','FLIGHT',4).

attribute('TYPE','PLANE',1).
attribute('SEATS','PLANE',2).
```

The following goal retrieves the name of the relation table corresponding to the Prolog database predicate functor `flight`/4 and the name of the attribute corresponding to the second argument of `flight`/4.

```
?- relation(flight,Table,_),attribute(Table,Attribute,2).

Table = 'FLIGHT'
Attribute = 'DEPARTURE'
```

♦

Note that type information could be included in the schema description in an additional argument. Such type information can only be used to check already during the translation whether a constant argument complies with the type of the corresponding database attribute. For the retrieval from the database such type information cannot be utilized because Prolog is an untyped language.

Example

Type information can be stored along with the attribute descriptions in `attribute`/4:

```
attribute('FLIGHT_NO','FLIGHT',1,'CHAR(5)').
```

♦

With typed logic languages, e.g. Gödel [Hill/Lloyd 91], type information could and should be exploited to facilitate detecting errors as soon as possible.

7.2.2 Translation of database access requests

In database set predicates implemented in Prolog and accessing relational databases, the database access language is a restricted sublanguage of Prolog equivalent in expressive power to relational calculus.

A database access request consists of a projection term and a database goal.

- A projection term is a term. Each variable in the projection term must also occur in the database goal.

Note that the projection term may be an arbitrarily complex term.

The database goal expresses the query to be evaluated by the database system. For relational databases, the operators union, intersection, difference, selection and join must be expressed through the database goal.

- A database goal contains positive or negative literals $L_1,\ldots,L_n$, $n \geq 1$, connected through the logical connectives "," and ";" such that
  - L_i is a database predicate, a comparison operation, or an arithmetic or aggregate function,
  - at least one L_i is a positive database predicate,
  - all input arguments of functions are bound,
  - all arguments of comparison operations are bound.

The functor of a database predicate is mapped to the appropriate relation table name, and each of the predicate arguments is assigned a relation attribute. The comparison operations in the database goal must be expressible in SQL. This is true for the standard comparison operations >, <, =, etc.

The allowed functors for aggregate functions are `sum`, `avg`, `min`, `max`, and `count`. Arithmetic functions are written using the functor `is`/2 in infix position as in `X is ArithmeticExpression` with `ArithmeticExpression` an evaluable arithmetic expression. Again, all arithmetic functions used in the database goal must be expressible in SQL.

Due to the order of execution imposed by the Prolog control strategy a complex database goal has as the first subgoal at least one call to a positive database predicate to return bindings for the variable arguments, followed by negated goals, comparison operations, or functions.

SQL queries

Recall from section 2.1.2 that an SQL query consists of at least a `SELECT` and a `FROM` part, with optional `WHERE`, `GROUP BY`, and `ORDER BY` parts. The keyword `DISTINCT`, which is used to eliminate duplicate entries in the result relation, is also optional. Optional parts are enclosed in curly brackets in the following simplified SQL grammar.

```
SELECT {DISTINCT} <columnlist>
FROM <tablelist>
{WHERE <conditionlist>}
{GROUP BY <columnlist>}
{ORDER BY <columnlist>}
```

`<tablelist>` is a list of relation table names with range variables, `<columnlist>` a list of constants or relation attributes qualified through relation names or range variables which uniquely identify a relation, and `<conditionlist>` a list of comparison operations or subqueries. The items in `<tablelist>` and `<columnlist>` are separated by commas, whereas the logical connectives $\wedge$ and $\vee$, written as `AND` and `OR`, are used in `<conditionlist>`.

Translation of database access requests to SQL queries

The translation of database access requests to SQL queries is done according to the following informal translation rules.

- A conjunction of database goals is translated to a single SQL query.
- Disjunctions of database goals are translated to several SQL queries connected through the `UNION` operator.
- Negated database goals are translated to negated existential subqueries (`NOT EXISTS <subquery>`) in the `WHERE` part.
- Goal functors other than comparison operators and function symbols are translated to relation names and assigned a unique identifier (*range variable*) in the `FROM` part of the query.
- Comparison operations and functions are translated to the equivalent SQL comparisons and functions over relation attributes or constant values.

- Variables in the projection term are translated to attribute names in the `SELECT` part of the query. These attributes are qualified by range variables. Variables occurring only once in the database goal are not translated.
- Shared variables, i.e. variables occurring in at least two base calls in the database goal, are translated to join-conditions in the `WHERE` part.
- Constant values in the database goal translate to comparison operations of the appropriate qualified relation attribute and the constant value in the `WHERE` part.
- Constants in the projection term are not translated.

Translation of higher-order constructs

Depending on the database set predicate additional rules may be used. For example, `db_setof`/3 returns a result relation for each binding of the free variables in the database goal, duplicates are eliminated from the result relation, and the result relation is sorted. This requires the use of a GROUP BY and an ORDER BY part in the query.

- Free variables, i.e. variables occurring only in the database goal, are translated to qualified attributes in the GROUP BY part.
- Free variables and the variables occurring in the projection term are translated to qualified attributes in the ORDER BY part. The order in which the free variables and the projection term variables occur determines the order according to which the result relation is sorted.
- The keyword DISTINCT is added to the SELECT part of the query.

With these rules, the translation of higher-order constructs to SQL is achieved.

Translation of aggregate functions

Aggregate functions may only appear in the SELECT part of an SQL query. In database set predicates this is expressed by a projection term which contains a variable to hold the result of the aggregate function, and a database goal with the aggregate function represented through a ternary term, the functor of which is one of `min`, `max`, `avg`, `count`, `sum` (see section 6.3.5 for an example).

The translation of aggregate functions is as follows:

- Aggregate functions, written as relations in the database goal, are translated to the corresponding aggregate functions in the SELECT part.

Optimization

In general, query optimization is left to the query optimizer of the database management system. However, one specific optimization is applicable during the translation already.

- Disjunctions of simple database goals need not always be translated to separate queries interconnected through UNION.
  If the disjunction concerns only comparison operations, then these comparison operations

can be included in the WHERE part by using OR instead of AND to connect the individual entries in the WHERE part.

This is best achieved by substituting in the database goal any constant argument by a variable, and appending to the database goal an equality comparison with that variable and the constant value. This amounts to factoring base calls out of a disjunction, so that only comparisons or arithmetic functions remain [Danielsson/Barklund 90].

7.2.3 SQL compiler

For the implementation of database set predicates a Prolog to SQL compiler has been built. The compiler is written entirely in Prolog, and is efficient. As a rule of thumb, the translation of a complex database goal with at least one join-condition and a comparison operation takes about as long as one access to the hard disk:

- approx. < 20 msec under LPA Mac Prolog 3.5 on a Mac II fx, and
- approx. < 10 msec under Quintus Prolog 3.0 on a SUN SPARCstation 1.

These timings are for a non-optimized compiler. The total code takes about 8 pages of Prolog code, one goal per line. Both the execution speed and the compact code compare favorably with compilers written in procedural languages, e.g. Modula-2.

The compiler directly reflects the compilation phases described by D.H.D. Warren [Warren 80] (Fig. 20. A).

Fig. 20. B displays the datastructures created during the translation: the compiler is called with a database access request consisting of a projection term and a complex database goal. Both terms may contain variable arguments. The lexical analysis transforms these terms into ground terms to prevent accidental instantiation of variable arguments during later translation steps. The ground database goal is then transformed into a logically equivalent disjunction of conjunctions in which negation appears only immediately before a simple goal. These conjunctions and the ground representation of the projection term are then passed on to the code generator to generate an intermediate structure which consists of separate lists of relation table names, qualified attributes and conditions for the SQL query. This intermediate structure yields a query term from which the final output is created.

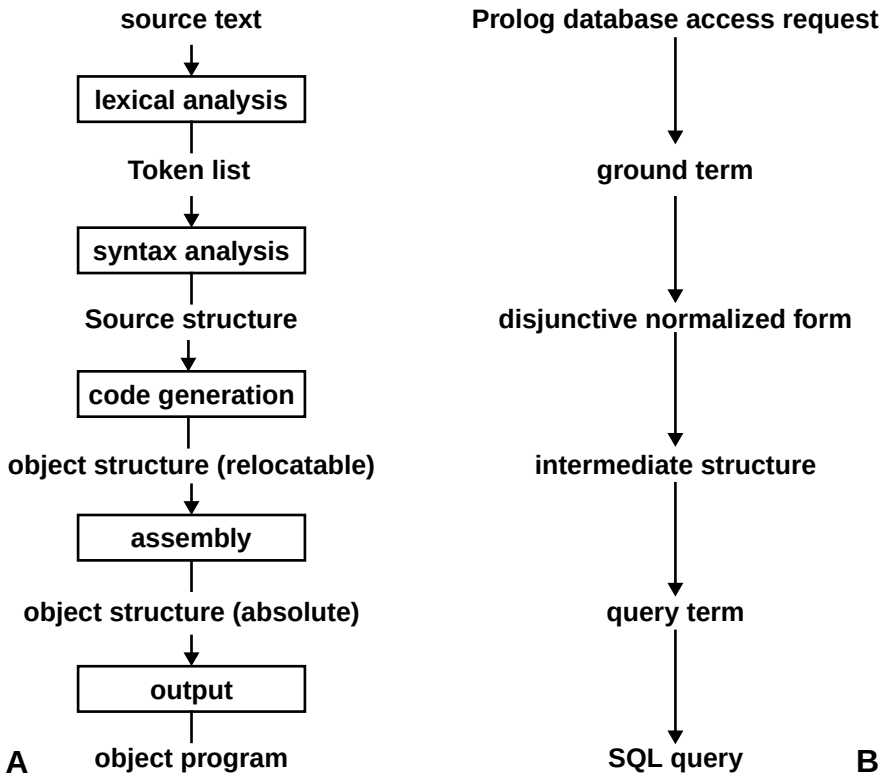


Fig. 20. Compilation phases

In this short overview, only the more interesting parts of the compiler are shown. On the top level, the compiler consists of the predicate `translate`/3:

```
% translate(ProjectionTerm,DatabaseGoal,SQLQueryTerm)

translate(ProjectionTerm,DatabaseGoal,Code):-
  % --- lexical analysis -----
  tokenize_selection(DatabaseGoal,TokenizedGoal),
  tokenize_projection(ProjectionTerm,TokenProjection),
  % --- syntax analysis ------
  push_negation_inside(TokenizedGoal,NegatedGoals),
  disjunction(NegatedGoals,Disjunction),
  % --- code generation ------
  code_generation(Disjunction,TokenProjection,Code),
  % --- output ---------------
  printqueries(Code).
```

During the lexical analysis of the projection term and the database goal in the subgoals `tokenize_selection`/2 and `tokenize_projection`/2 any variable is instantiated with a term `var(VarId)`, where `VarId` is a unique identifier generated by `gensym`/2. Through this instantiation identical variables in the whole clause are given the same identifier.

```
tokenize_argument(var(VarId),var(VarId)):-
  % first argument is a variable - it is instantiated with
  % the term var(VarId) throughout the original goal
  gensym(var,VarId).
```

Constants in the database goal and the projection term are replaced by a term `const(ConstantValue)` with `ConstantValue` the original value of the constant. This simplifies the distinction between constants and variables in later processing steps. After the lexical analysis both the projection term and the database goal are represented by ground terms.

In the syntax analysis phase any negations are pushed into the database goal until negation operators appear in front of simple goals only. This is achieved through the application of de Morgan's laws, as in (only one clause shown here)

```
push_negation_inside(not (A,B),(NegA;NegB)):-
  push_negation_inside(not A,NegA),
  push_negation_inside(not B,NegB).
```

This transformed database goal is then split into a disjunction of base conjunctions, and is represented as a list with each base conjunction a list item.

The code generation predicate takes as input the list of base conjunctions and the projection term. Each such conjunction is translated to an SQL query, represented as a term `query`/5. All such terms are collected in a list.

```
% code_generation(Conjunctions,ProjectionTerm,Queries)

code_generation(Conjunctions,ProjTerm,Queries):-
  % --- calls code_generation/4 with a new Dictionary
  code_generation(Conjunctions,ProjTerm,Dictionary,Queries).



% code_generation(Conjunctions,ProjectionTerm,Dictionary,Queries)

code_generation([],_,_,[]).

code_generation([DBGoal|DBGs],ProjTerm,Dict,[Query|Qs]):-
  translate_selection(DBGoal,FromPart,WherePart,Dict),
  translate_projection(ProjTerm,Dict,SelectPart),
  translate_grouping(ProjTerm,DBGoal,Dict,GroupPart),
  translate_ordering(ProjTerm,DBGoal,Dict,OrderPart),
  Query=query(SelectPart,FromPart,WherePart,GroupPart,OrderPart),
  code_generation(DBGs,ProjTerm,Qs).
```

`code_generation`/3 calls `code_generation`/4 with an empty dictionary. This dictionary is constructed during the translation and contains the mapping to the corresponding qualified relation attribute for each variable in the database access request. This dictionary is valid for the translation of one conjunction only. Hence, `code_generation`/3 is called for the remaining disjunctions in the last clause of `code_generation`/4 and a new dictionary is created for the next conjunction.

Nested subqueries use the same dictionary as the original query. Thus, the translation of a nested subquery calls `code_generation`/4 directly with the current dictionary.

`translate_selection`/4 as the first subgoal in the body of `code_generation`/4 takes as input a base conjunction and returns a list of relation table names, a list of selection conditions, and the dictionary. The base conjunction contains simple database goals, all of which are ground terms. Simple database goals are transformed to a list through `=..`/2, and the functor and its arguments are translated separately:

```
translate_selection(SimpleDBGoal,[From],Where,Dict):-
  SimpleDBGoal =.. [Functor|Arguments],
  translate_functor(Functor,From),
  selection_argument(Arguments,From,1,Where,Dict).
```

Every functor other than a comparison operator or a function symbol in the database goal is assigned a unique range variable and is added to the list of relation table names:

```
translate_functor(Functor,rel(RelationName,RangeVariable)):-
  relation(Functor,RelationName,Arity),
  gensym(rel,RangeVariable).
```

`translate_arguments`/5 simply organizes the translation of the list of arguments. The translation itself is implemented by `selection_argument`/5. In this translation, three cases must be distinguished: An argument may either be

- a variable which is not yet stored in the dictionary,
- a variable which is stored in the dictionary already, or
- a constant value.

A term `var(VarId)` is added once to the dictionary along with the corresponding range variable and the attribute name of the goal in which it occurs first. If a term `var(VarId)` is in the dictionary already, this means that this variable has occurred in a previous goal which must be different from the current goal. This is a join expression, which is translated to a join condition in the condition list. A term `const(Const)` is translated to an equality comparison and added to the condition list.

```
% selection_argument(Argument,Relation,Position,Where,Dictionary)
% maps argument position to qualified attribute names and builds
% conditions list

selection_argument(var(VarId),rel(Rel,RangeVar),Pos,[],Dict):-
  attribute(Rel,Attribute,Pos),
  % new var(VarId): add to dictionary with table name and pos
  lookup(VarId,Dict,RangeVar,Attribute),
  !.
```

```
selection_argument(var(VarId),rel(Rel,RangeVar),Pos,JoinCond,Dict):-
  % var(VarId) in dictionary already: equality test in WHERE part
  lookup(VarId,Dict,PrevRangeVar,PrevAtt),
  PrevRangeVar \= RangeVar,
  attribute(Rel,Attribute,Pos),
  JoinCond =
  [comp(att(RangeVar,Attribute),=,att(PrevRangeVar,PrevAtt))].

selection_argument(const(Const),rel(Rel,RangeVar),Pos,CompOp,Dict):-
  % translate to test: attribute = constant value
  attribute(Rel,Attribute,Pos),
  CompOp = [comp(att(RangeVar,Attribute),=,const(Const))].
```

The translation of comparison operations and arithmetic functions follows the translation of simple database goals. The main difference is that the operands may be evaluable expressions instead of simply variables or constant values. Such evaluable expressions, which may contain variables, are not evaluated by Prolog. Instead, they are translated to SQL evaluable expressions with the variables replaced by relation attributes.

The projection term is translated by `translate_projection`/3. The input arguments are ground representation of the projection term and the dictionary. The result is a list of qualified attribute names in a list in the argument `SelectPart`. The projection term may only contain variables which also occur in the database goal too. Because the database goal is translated prior to the projection term, and because the dictionary contains all variables occurring positively in the database goal, the mapping of all variables occurring in the projection term is already contained in the dictionary. The translation of the projection term is thus straightforward: constant values are added to the list unchanged, and variables are substituted by qualified attribute names.

```
translate_projection(ProjectionTerm,Dictionary,SelectList):-
  ProjectionTerm =.. [Functor|Arguments],
  projection_arguments(Arguments,SelectList,Dictionary).
```

`projection_arguments`/3 organizes the translation of projection term arguments by working through the list of arguments recursively. The translation itself is performed by `projection_argument`/3.

```
projection_argument(var(VarId),att(RangeVar,Attribute),Dict):-
  lookup(VarId,Dictionary,RangeVar,Attribute).

projection_argument(const(Const),const(Const),_).
```

For the `GROUP BY` and the `ORDER BY` part of the final query the free variables in the database goal must be handled. This is done in `translate_grouping`/4 and `translate_ordering`/4. Unfortunately SQL places severe restrictions on the use of groupings. Only such attributes may be included in the `SELECT` part of a grouped query that have a single value for each grouping attribute. This effectively restricts the use of grouping to aggregate functions which compute one single value for a grouped attribute.

In the last two subgoals of `code_generation`/4 the query term for the current conjunction of database goals is constructed, and the recursive call to `code_generation`/3 continues the computation with the next conjunction of goals.

7.2.4 Comprehensive Example

The database request is:

> "Retrieve from the database the departures and destinations connected by flights with large planes, i.e. planes with more than 150 seats. Print the departures, destinations, planes and the respective number of seats in alphabetical order".

With database set predicates, this request is written as:

```
?- db_setof((Departure,Destination,Plane,Seats),
     FlightNo^
     (flight(FlightNo,Departure,Destination,Plane),
      plane(Plane,Seats),
      Seats > Bound),
    List).
```

Although `Bound` is a variable, it must be bound to a constant value, in this case 150, prior to the call of the database set predicate. Otherwise the comparison operation would have an unbound operand.

The projection term is

```
(Departure,Destination,Plane,Seats)
```

and the database goal is

```
FlightNo^
  (flight(FlightNo,Departure,Destination,Plane),
   plane(Plane,Seats),
   Seats > 150)
```

The projection term and the database goal are translated to the following ground representation by the lexical analysis:

```
(var(var1),var(var2),var(var3),var(var4))
```

and

```
var(var0)^
(flight(var(var0),var(var(1),var(var2),var(var3)),
 plane(var(var3),var(var4)),
 var(var4) > const(150))
```

The syntax analysis leaves the ground representation of the database goal unchanged because it does not contain disjunction or negation. The list of base conjunctions thus contains only one entry, namely the database goal.

The ground representations of the projection term and the database goal serve as input to `code_generation`/3. The result of the code generation is a list containing only one query term with five list arguments (for the SELECT, FROM, WHERE, GROUP BY and ORDER BY part of the final query). `f` and `p` are range variables which uniquely identify the relation tables `flight` and `plane`.

```
[query(
 [att(f,departure),att(f,destination),att(f,plane),att(p,seats)],
 [rel(flight,f),rel(plane,p)],
 [comp(att(f,plane),=,att(p,type)),comp(att(p,seats),>,const(150)],
 [],
 [att(f,departure),att(f,destination),att(f,plane),att(p,seats)]
)]
```

The final output of the compiler is the following SQL query:

```
SELECT DISTINCT f.departure,f.destination,f.plane,p.seats
FROM flight f, plane p
WHERE f.plane = p.type and p.seats > 150
ORDER BY f.departure,f.destination,f.plane,p.seats
```

Any instantiation of a template variable would lead to a more restrictive query. With `Departure` bound to the constant `zurich`, the query would be

```
SELECT DISTINCT zurich,f.destination,f.plane,p.seats
FROM flight f, plane p
WHERE f.departure = "zurich" and f.plane = p.type and p.seats > 150
ORDER BY zurich,f.destination,f.plane,p.seats
```

♦

7.3 Realization of the communication channel and its interfaces

In a physically loosely coupled system a Prolog system is connected to an external database system via a communication channel. This communication channel can be realized through either

- procedure calls or
- inter-process communication

Ideally, the communication channel is completely hidden from the Prolog system, and only Prolog datastructures are written into or read from the communication channel. For database set predicates this would mean that the subgoal `evaluate_in_db`/2 writes a term into the communication channel, and retrieves a list of instantiated terms from the channel. In practice, however, database systems do not offer a direct interface to Prolog (or to declarative languages in general), and thus the communication channel has to be programmed explicitly.

7.3.1 Inter-process communication

With Prolog and the database system separate processes communication between them can be achieved through inter-process communication via operating system communication devices such as pipes or streams (Fig. 21.).

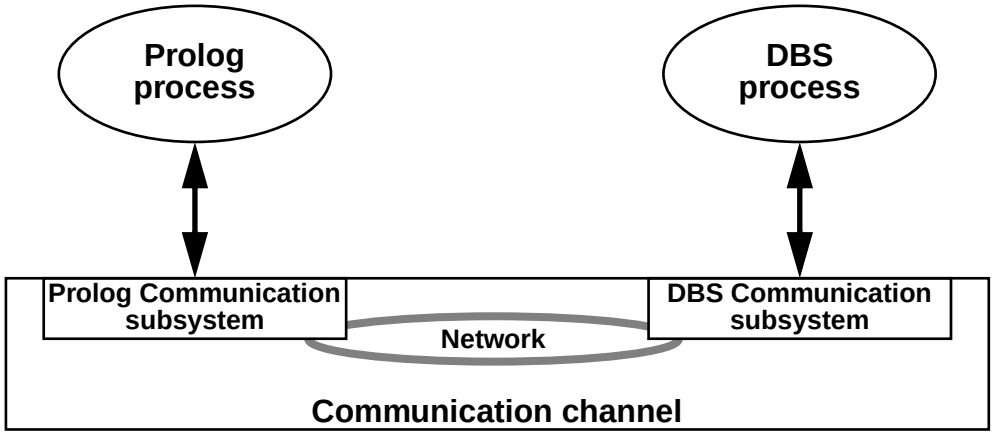


Fig. 21. Inter-process communication between a Prolog and a database system process

In coupled systems of this type the database access procedure is as follows: the database goal is translated to a query string by Prolog. This string is sent to the communication subsystem in the operating system to which the Prolog process is connected. From this communication subsystem the query is transmitted via a network to the communication subsystem of the database system, from which it is sent to the database system. The query is evaluated by the database system, and the result relation is returned to the communication subsystem. The data is transmitted via the network to the Prolog communication subsystem from which it is returned to the Prolog system itself.

Inter-process communication is based on the exchange of single characters, or sequences of characters. This data must be interpreted in the interfaces on either side of the communication channel. In the database system the user interface can provide the required interpretation. In Prolog, a parser and a tokenizer must be implemented.

A *tokenizer* interprets the incoming characters and transforms them into Prolog terms. This tokenizing step can be implemented in Prolog through the use of the basic character input predicates `get`/1 or `get0`/1, and the system predicate `name`/2 which succeeds if its second argument contains the ASCII codes of the printed representation of its first argument in a list. `name`/2 may be used to translate lists of characters to Prolog atoms and vice versa, and thus effectively implements a tokenizer already.

The tokenizer is called by a *parser* which maps the tokenized terms to the projection term. For every argument in the projection term there must be an attribute value in each row of the result relation.

The parser takes as input the projection term, which in the SQL compiler is a term with its arguments either `var(VarId)` or `const(Constant)`. The output is a term with the same functor and arity as the projection term, but all arguments substituted with attribute values retrieved from the database system. The parser calls the tokenizer for each argument in the projection term, and the parser itself is called for every row of the result relation.

```
parse(ProjectionTerm,InstantiatedTerm):-
  ProjectionTerm =.. [Functor|Arguments],
  not member(Functor,[var,const],
  parse_arguments(Arguments,Instantiation),
  InstantiatedTerm =.. [Functor|Instantiation].


parse_arguments([],[]).

parse_arguments([var(_)|Args],[Value|Vs]):-
  tokenize(Value),
  parse_arguments(Args,Vs).

parse_arguments([const(_)|Args],[Constant|Vs]):-
  tokenize(Constant),
  parse_arguments(Args,Vs).

parse_arguments(Term,InstantiatedTerm):-
  parse(Term,InstantiatedTerm).
```

The instances of the projection term are then collected in a list.

7.3.2 Communication via procedure calls

Most commercial database systems provide *programming language interfaces* for procedural programming languages, e.g. Pascal or C. Through such an interface, application programs written in a procedural programming language access the database system via function or procedure calls.

Prolog systems in general feature a *foreign language interface* to procedural languages. Predicates can be defined in external procedural programming languages, and a call to such a predicate results in a procedure call to the external programming language. Data is exchanged via the arguments of the predicate.

This makes possible coupled systems in which the Prolog system accesses the database system indirectly through calls to externally defined procedures (Fig. 22.).

In coupled systems of this type the database access procedure is as follows: the database query is formulated in Prolog and passed on to the procedural language as a procedure call through the foreign language interface. A data conversion program written in the procedural language transforms the Prolog compatible datastructures into datastructures accepted by the database system, and calls the appropriate database functions of the programming language interface of the database system. The result of the database evaluation is returned to the procedural programming

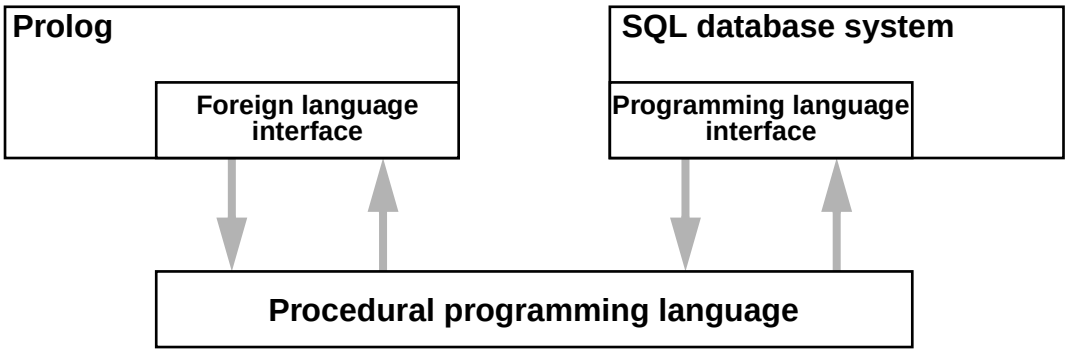


Fig. 22. Communication between Prolog and a database system via procedure calls

language and placed in a dynamic datastructure from which it is transformed into a datastructure accepted by Prolog. This datastructure is returned to Prolog as the result of the original goal.

In the procedural language database cursors are used to retrieve data from a database system. A cursor is defined as a record datastructure in the procedural programming language. When the database is accessed, the cursor is opened. Database records are retrieved from the database system and written into the cursor datastructure. A dynamic datastructure is used to store a whole result relation. Initially, this dynamic datastructure is instantiated by a null value. In a loop the database records of the result relation are retrieved one after the other and added to the dynamic datastructure. As soon as the result relation is exhausted the database cursor can be dropped.

A sample interface program written in Pascal could be implemented as shown in Fig. 23.(the transformation procedures from the representation of Prolog terms to a datastructure of the procedural language and vice-versa are assumed to be pre-defined):

Note that this use of cursors does not lead to the control flow problems discussed in section 6.3.1. Here a cursor is alive for the retrieval of one relation only, and it is dropped immediately upon having reached the end of the relation. This fully complies with the simple distribution of control in database set predicates.

The major appeal of using a procedural programming language to connect a Prolog system with a database system is that the interfaces between Prolog and the procedural language, and between the procedural language and the database system are defined already.

```
program database_access;
type
    db_cursor_type = record
    < list of attribute datastructures >
    end;
relation = record
    data : db_cursor_type;
    next : ↑relation;
    end;

procedure db_access(In:PrologType; var Out:PrologType);
var  result, tuple : relation;
    cursor : db_cursor_type;
    db_args : < datastructure for query >;
begin
(* transform Prolog compatible to database compatible types *)
Prolog_to_DB(In, db_args),

result := nil;
db_call(db_args);
db_open_cursor(cursor);

while db_fetch_cursor(cursor) do
    begin
    new(tuple);
    tuple↑.data := cursor;
    tuple↑.next := result;
    result := tuple;
    end; (* end while loop *)

db_drop_cursor(cursor);

(* transform database compatible to Prolog compatible types *)
DB_to_Prolog(result,Out);
end;

begin (* dummy main program - procedures are called from Prolog *)
end.
```

Fig. 23. Sample procedure call interface program for accessing external databases

7.3.3 Comparison of methods

Communication via procedure calls and inter-process communication are two fundamentally different concepts.

- With communication via procedure calls the coupled system effectively is a single operating system process, whereas with inter-process communication there are several operating system processes which may run in parallel. Potentially, even a distributed coupled system is implementable by having the processes run on different machines.
- With communication via procedure calls, the level of data exchange is that of Prolog terms, whereas with inter-process communication data is exchanged on the level of character sequences which must be interpreted.

Data conversion

The problem of data conversion between Prolog and database data formats occurs independently of the approach to communication.

Prolog systems generally are tagged architectures. A small fragment of the memory allocated for a data item contains a tag with type information, the rest is used for the value itself. In database systems, type information is held in the schema, and the full width of a machine word can be used for the representation of a value. This difference in the number of bits available in the database system and Prolog leads to different value ranges, and to different precisions in the computation of real or floating point numbers. The range of values must thus be restricted to the largest common range of values.

A second problem is that some datastructures of the one system are not known in the other. For example, SQL features a multitude of different number formats, whereas most Prolog systems only distinguish between floating point numbers and integers. Consequently, some datastructures may not be adequately represented, or different datastructures of the database system are represented through identical datastructures in Prolog.

These problems are common to both types of communication. With a procedure call interface they are perhaps more severe because there is an additional data conversion step in the procedural language. Clearly, this additional interface increases the likelihood of data conversion problems.

Efficiency and flexibility

Efficiency and flexibility are dependent on the approach to communication. With inter-process communication the amount of data handled is larger by approximately an order of magnitude than with procedure calls because sequences of individual characters are considered instead of high-level terms. The interpretation of data is performed on both sides of the communication channel, but for this efficient built-in conversion mechanisms can be used.

With procedure calls three conversions are necessary: from the internal representation of the database system to an appropriate datastructure in the procedural language, from this representation to one suitable for Prolog, and from this representation in the procedural language

to true Prolog terms. The first and the last data conversion is provided by the programming language interface in the database system and the foreign language interface in Prolog respectively. However, the transformation of database system compatible datastructures to those accepted by Prolog (and vice versa) must be programmed explicitly.

The major difference between the two approaches is that database access through procedure calls must be defined statically at compile time already whereas with inter-process communication database access is defined dynamically at runtime.

In a procedural language a record datastructure serves to capture the data retrieved by the database cursor. This record datastructure is defined statically as part of the program. As a consequence, a different cursor type definition is necessary for every different projection on database relation tables. Using a procedural language as an interface to the database system thus makes sense when the projection on database attributes is known at compile time already. This is not the case with database set predicates, because both the projection term and the database goal are constructed dynamically. Hence, communicating via procedure calls severely restricts the dynamic query formulation capacities of database set predicates.

This problem is further aggravated by the fact that the datastructures used in the foreign language interface in the Prolog system and those of the programming language interface in the database system are highly system dependent and thus in the general case not portable.

With inter-process communication, a parser combines the tokenized input from the database system to complex terms which are instantiations of the projection term with database values. Because term construction can be done dynamically, constructing different terms in which the database values are stored is possible at runtime. However, parser and tokenizer must be defined statically or be provided by the Prolog runtime system.

Conclusion

The dichotomy between procedure call and inter-process communication can be expressed in terms of dependencies: system implementation dependency vs. operating system dependency.

For every combination of a Prolog system and a database system implementation the procedure call interface has to be defined anew. Currently, there is neither a standard for a programming language interface for relational database systems, nor for foreign language interfaces in Prolog systems. Porting a database set predicate implementation to a different configuration of a Prolog and a database system thus implies considerable implementation effort and may even require modifications in the application program because of the static database access definition.

With inter-process communication the presence of operating system communication devices determines whether a particular implementation of database set predicates can be ported to other machines. The Prolog and the database system do not communicate with each other directly, but only with the interface to the operating system communication devices. Thus, replacing one database system for another one has no effects on the Prolog system (modifications, if any, are

restricted to the parser and tokenizer which must parse the data retrieved from the database system).

8

A Real-World Application: Synthesis Planning with DedChem

8.1 Introduction

I now present a real-world problem which is handled elegantly with a coupled system based on database set predicates. The application domain is organic chemistry, and the task is that of planning the synthesis of a specific substance class on the basis of name reactions. A synthesis plan contains the reactions that are necessary to synthesize a given substance, the order in which the individual reactions must be performed, and the intermediate substances which are synthesized as by-products during the synthesis.

Synthesis planning corresponds to computing the transitive closure of a reaction relation under application dependent constraints. The synthesis plan itself may be represented as a tree structure, with the nodes standing for intermediate substances, and the edges standing for reactions.

A coupled system based on Prolog provides the required expressive power for the representation of the reaction relation, the synthesis plan, and for the implementation of the deduction component to compute the transitive closure. The ease of implementation in a single high-level logic language implies a logically tightly coupled system. Practical constraints, e.g. access to a variety of reaction databases, demand a physically loosely coupled system.

8.1.1 Name reactions

*Name reactions a*re reaction prototypes or reaction schemes which are so commonly used that they are referred to by their name — often the name of the persons that discovered the reaction — instead of the substance classes involved. Name reactions thus describe standardized reactions which have proven to be useful in practice.

Name reactions abstract from concrete reactions in that they are defined for substance *classes*, not individual substances. A name reaction thus produces a certain substance class, the *product*, from one or two substance classes, the *educts*.

Name reactions are uniquely identified through their name and the substance classes involved. A full description of a name reaction contains a description of the reaction mechanisms, specific constraints and properties, and references. Typical constraints are temperature, pressure, the presence of specific reagents, and incompatibilities with substance classes, e.g. “in the presence of *X* the name reaction *Y* cannot be carried out”. Properties of a name reaction are yield, cost, toxicity, and others.

They may be represented as a directed graph, with the nodes standing for substance classes, and the edges labelled with the reaction name (Fig. 24. A). There exist cyclic name reactions that yield a product of the same class as one of the educts (Fig. 24. B).

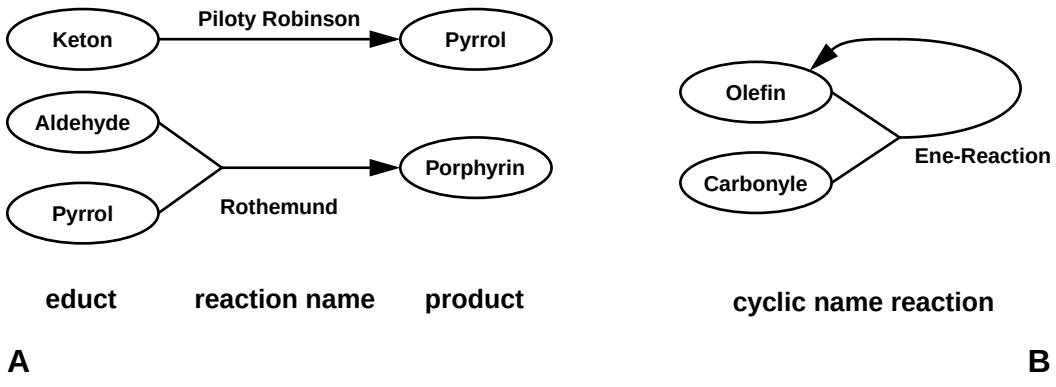


Fig. 24. Name reactions represented as directed graphs

A *substance class* groups together individual substances according to common structural properties. The class membership for a given substance is determined by its substructures. It is possible for a specific substance to belong to several substance classes depending on the substructure considered for the class membership.

Substance classes are arranged in a class hierarchy, and there may exist synonyms for a given substance class name. As classes may have common subclasses this hierarchy is a directed cyclic graph (Fig. 25.).

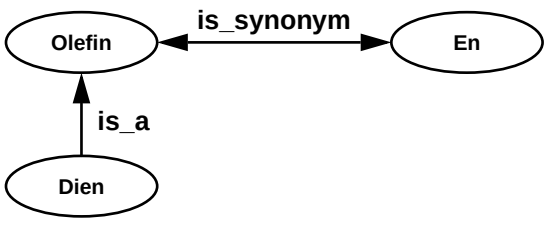


Fig. 25. Superclass and synonym relationships of substance classes

8.1.2 Synthesis tree

A *synthesi*s is the production of a specific substance class through a chaining of name reactions. The collection of all reaction chains resulting in the same substance class is called a *synthesis tree* for that substance class. In this synthesis tree, the product of one name reaction is the educt of another name reaction on the next higher level in the tree. The root of the tree is the substance class that is to be synthesized, and the leaves of the tree contain the substance classes needed for this particular synthesis. The synthesis tree may contain duplicate nodes and subtrees.

Each branch in the tree from the leaves to the root represents a reaction chain or *synthesis plan* (Fig. 26.).

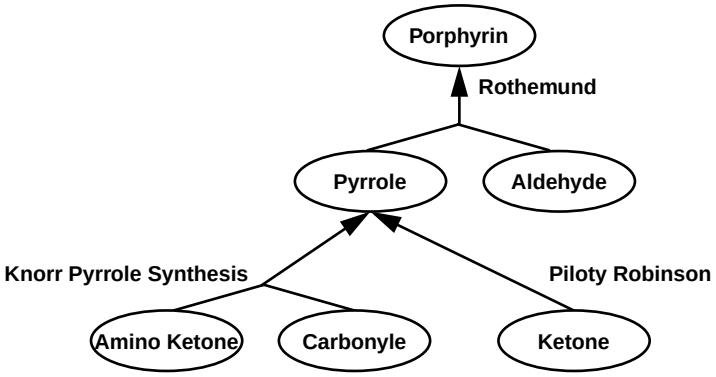


Fig. 26. Fragment of the synthesis tree for a porphyrin with two branches

Synthesis planning is *retrosynthetic* if the planning starts with a product and proceeds with the educts.

A synthesis tree is constructed by computing the *transitive closure* of name reactions. This computation must respect the specific properties of name reactions:

- Name reactions with two educts require the computation of the transitive closure for the name reactions of *both* educts.
- Cyclic name reactions are allowed. However, the length of any cycle must not exceed a given limit.
- Synonym and superclass relationships require the computation of the transitive closure for the synonym or the superclass of a substance class.

8.1.3 A first implementation of `synthesis/3`

Basically, the algorithm used to compute the transitive closure of name reactions is a double recursive variant of the path-finding algorithm known from the literature. This algorithm searches for a synthesis retrosynthetically, i.e. from the root of the synthesis tree. The current path from the root to subsequent nodes is passed as an argument to allow checking for cycles.

In the following naive implementation of `synthesis`/3 name reaction and superclass relations are represented as the extensionally defined predicates `reaction`/3 and `is_a`/2:

```
% --- reaction(Product, Educt, ReactionName) --------

reaction(porphyrin,(pyrrole,aldehyde),rothemund).
reaction(pyrrole,ketone,piloty_robinson).
...

% --- is_a(SubstanceClass, SuperClass) --------------

is_a(dien,olefin).
...
```

`valid_reaction`/2 checks whether a given reaction name is in the current path already (thus avoiding cycles altogether. Checking only the first `m` elements of the path with length `len`, with `m = len - n`, allows limiting the length of cycles to `n`). The path is constructed bottom-up, whereas the current branch of the synthesis tree is built top-down. Initially, the path is the empty list. Note that synonym relations are not considered in this simple program.

If there exist name reactions with the current substance class as product, a valid name reaction is selected, and the search continues with the educts of the reaction. There is a clause for name reactions with single educts, and a clause for name reactions with two educts.

```
synthesis(Substance,Path,node(Substance,ReactionName,Tree)):-
  reaction(Substance,Educt,ReactionName),
  % --- make sure Educt is a simple educt ------
  atomic(Educt),
  valid_reaction(ReactionName,Path),
  synthesis(Educt,[ReactionName|Path],Tree).

synthesis(Substance,Path,node(Substance,ReactionName,Left,Right)):-
  reaction(Substance,(Educt1,Educt2),ReactionName),
  valid_reaction(ReactionName,Path),
  synthesis(Educt1,[ReactionName|Path],LeftTree),
  synthesis(Educt2,[ReactionName|Path],RightTree).
```

If there is no reaction with the current substance class as product, then the search continues with its superclass.

```
synthesis(Substance,Path,SubTree):-
  is_a(Substance,SuperClass),
  synthesis(SuperClass,Path,SubTree).
```

Otherwise, if there is no reaction with the current substance as product and no superclass of the current substance, the computation terminates and the current substance class is returned as a leaf.

```
synthesis(Substance,_,leaf(Substance)):-
  not reaction(Substance,_,_),
  not is_a(Substance,_).
```

A synthesis planning session is started by the rule `synthesis`/2

```
synthesis(Substance,SynthesisBranch):-
  synthesis(Substance,[],SynthesisBranch).
```

Example

For planning the synthesis of the substance class `porphyrin`, the goal is

```
?- synthesis(porphyrin,SynthesisBranch).
```

and the two branches of the synthesis tree shown in Fig. 26. would be returned as follows:

```
SynthesisBranch =
  node(porphyrin,rothemund,
   (node(pyrrole,piloty_robinson,
    leaf(ketone)),
   leaf(aldehyde))) ;

SynthesisBranch =
   node(porphyrin,rothemund,
    (node(pyrrole,knorr_pyrrole_synthesis,
     (leaf(amino_ketone),
      leaf(carbonyle))),
    leaf(aldehyde))) ;

no more solutions
```

♦

8.2 DedChem — a coupled system for synthesis planning

The goal of synthesis planning consists in finding a chain of individual reactions which is optimal according to specified criteria, e.g. yield, cost, or others. Synthesis planning is an iterative process: A first plan is devised, and this plan is then evaluated. If the plan is plausible, then the synthesis can actually be carried out. If not, a new plan has to be devised.

Students learn to plan syntheses during their formal education. With little experience to guide them, this learning consists of spending days in the library, browsing through a name reaction dictionary and constructing synthesis plans. For an experienced chemist, matters are not very different: an experienced chemist is comfortable with only a few dozen name reactions. Thus, confronted with a the task of planning the synthesis of a substance which is new to her or him, she or he joins the students in the library.

DedChem is a coupled system for synthesis planning in organic chemistry which is being developed in collaboration with the organic chemistry institute at the university of Zurich. **DedChem** supports experts and students in the process of synthesis planning. The system contains a name reaction dictionary in external databases, and a deduction component written in Prolog which chains the individual reactions and constructs the synthesis tree. Search can be restricted by either disallowing or by explicitly requiring specific substances or reactions in the synthesis tree. **DedChem** is currently implemented as a prototype on a Macintosh computer [Draxler 90].

8.2.1 Database for substance classes, superclasses and name reactions

The quantitative requirements for a synthesis planning system based on name reactions are fairly low. The name reactions known to date number little more than 1000. As some name reactions are defined for more than one combination of substance classes, the total number may be slightly higher. Name reactions are never deleted from the database, so that their number steadily increases. There are approximately 1000 different substance classes. Again, this number is rather low from a database point of view.

Although the amount of data such a system will have to handle is rather small, a true database system should be used because of the known database security and integrity features and multi-user access. This is particularly interesting in a laboratory environment, where there is a central database, and potentially many users who wish to access the database from their workbench or desk.

In **DedChem**, the name reactions, substance classes, superclasses, and synonyms are stored in external relational databases. Any additional information related to name reactions, e.g. yield, cost, toxicity, basic mechanism, references, etc. are stored in separate relation tables with the reaction name as key. These relation tables are mapped to the Prolog database predicates `reaction`/3, `substance`/1, `is_a`/2, `is_synonym`/2, and `reaction_information`/4.

Note that name reactions may have one or two educts which may lead to the following problems: Storing both educts in a single attribute violates the first normal form of the relational database model. Providing two attributes in the reactions table will result in null values for reactions with only one educt. Finally, using two distinct relation tables, one for reactions with one educt, the other for reactions with two educts, causes considerable administration overhead. In **DedChem**, the first alternative has been chosen. The educts of a name reaction are stored in a single attribute, with the decomposition into single educts done by Prolog. This facilitates accessing the database from Prolog. Furthermore, with NF^2 database systems becoming available, structured attributes will be supported by the underlying database system.

8.2.2 Database set predicates for database access

The basic algorithm of section 8.1.3 has two major drawbacks:

- it requires a very large number of individual database access requests (one access request in every clause), and
- the solutions are returned in the order in which the database records are stored in the relation tables.

These problems can be solved through the incorporation of database set predicates. The first step is to separate the individual database accesses from the computation of the transitive closure by collecting the database access requests in a single predicate clause. In the second step, database set predicates are introduced to allow reordering the items retrieved from the database.

Collecting database accesses in a predicate of its own

The recursive predicate `synthesis`/3, which in every clause contains an access to the database, is rewritten as two mutually recursive predicates `db_retrieve`/3 to access the database, and `synthesis`/3 to construct the synthesis tree:

```
db_retrieve(Substance,Path,Tree):-
  reaction(Substance,Educt,Name),
  synthesis((Substance,Educt,Name),Path,Tree).

db_retrieve(Substance,Path,Tree):-
  is_a(Substance,SuperClass),
  synthesis((Substance,SuperClass),Path,Tree).

db_retrieve(Substance,_,Substance):-
  not reaction(Substance,_,_)
  not is_a(Substance,_).

synthesis(Reaction,Path,node(Substance,ReactionName,SubTree)):-
  Reaction = (Substance,Educt,ReactionName),
  atomic(Educt), % make sure Educt is a simple educt
  valid_reaction(ReactionName,Path),
  db_retrieve(Educt,[Substance|Path],SubTree).

synthesis(Reaction,Path,node(Substance,ReactionName,Left,Right)):-
  Reaction = (Substance,(Educt1,Educt2),ReactionName),
  valid_reaction(ReactionName,Path),
  db_retrieve(Educt1,[Substance|Path],Left),
  db_retrieve(Educt2,[Substance|Path],Right).

synthesis((Substance,SuperClass),Path,Tree):-
  db_retrieve(SuperClass,Path,Tree).
```

A closer look at `db_retrieve`/3 reveals that each backtracking leads to a further access to the database because only one record is fetched at a time.

Introducing database set predicates

With database set predicates the database is accessed only once for the retrieval of reactions and superclass relationships respectively. An additional benefit is that the order in which reactions and superclass relationships are retrieved is determined by the application program, and not by the order of records in the database.

All reactions for a given substance are read in at once, and one by one is returned through backtracking over the list. Only after the reactions have been exhausted the superclass relationships are read in.

```
db_retrieve(Substance,Path,Tree):-
  db_setof((Substance,Educt,Name),
   reaction(Substance,Educt,Name),ReactionsList),
  member((Substance,Educt,Name),ReactionsList),
  synthesis((Substance,Educt,Name),Path,Tree).
```

```
db_retrieve(Substance,Path,Tree):-
  db_setof((Substance,SuperClass),
   is_a(Substance,SuperClass),SuperClassList),
  member(SuperClass,SuperClassList),
  synthesis(SuperClass,Path,Tree).

db_retrieve(Substance,_,Substance):-
  not reaction(Substance,_,_),
  not is_a(Substance,_).
```

Note that in the third clause the reactions database is accessed again to make sure that there does neither exist a reaction for the current substance, nor a superclass relationship. This database access, which in fact is a negated existence test for matching tuples, is expensive because it leads to the re-evaluation of a query that has been already answered.

Eliminating the existence test

The existence test `?- not reaction(...), not is_a(...)` in the third clause can be omitted if it is clear that all relevant database records have been retrieved before this clause is tried. If any reactions or superclass substances for the current substance have been retrieved from the database, it is clear that the existence test for this substance must fail. Alternatively, if no reactions and no superclass substances could be retrieved from the database, then it is clear that no matching records exist. Consequently, the test is superfluous and can hence be eliminated from the clause.

In Prolog, the pruning operators cut `!`/1 or if-then-else `->`/2 may be used to prevent alternative clauses from being entered by the interpreter. Because both operators are procedural constructs their position in the clauses defining a predicate is crucial. It is advisable to place them as early as possible, preferably immediately after the subgoal which has determined that no alternative to the current clause is to be tried [O'Keefe 90].

In the current version of db_retrieve/3, however, there is no possibility to place the cut or the if-then-else to achieve the desired behavior. A closer analysis reveals that the problem is due to the implicit disjunction of the three clauses: either reactions *or* superclass relationships may be used to continue the evaluation. The third clause may be evaluated if and only if there are no reactions *and* no superclass substances.

This problem is overcome by defining the new predicates `db_access`/3 and `select`/4 which are called by `db_retrieve`/3. `db_access`/3 is defined to always succeed. It returns a list which contains either the result relation corresponding to the goal argument, or which is the empty list.

```
db_access(Template,Goal,List):-
  (db_setof(Template,Goal,List) -> true
  ;
   List = []).

select([],Substance,_,Substance).

select(ItemList,Substance,Path,Tree):-
  member(Item,ItemList),
  synthesis(Item,Path,Tree).
```

`db_retrieve`/3 now retrieves all matching reactions and superclasses in lists and appends these lists to result in one list containing all items retrieved from the database. The existence test is now implemented by `select`/4 through the unification in the head of the clauses: an empty list means that no records have been retrieved and that the computation terminates. Otherwise, an item is selected from the list and the computation continues.

```
db_retrieve(Substance,Path,Tree):-
  db_access((Substance,Educt,Name),
   reaction(Substance,Educt,Name),ReactionsList),
  db_access((Substance,Superclass),
   is_a(Substance,Superclass),SuperClassList),
  append(ReactionsList,SuperClassList,ItemList),
  select(ItemList,Substance,Path,Tree).
```

The result of the transformations is a program in which there is only one clause accessing an external database. The number of database accesses is minimized, and the database is no longer accessed for existence tests, i.e. accesses which do not return data but require the evaluation of a query. Despite the if-then-else construct (which is indispensable because it makes the database access deterministic) the flow of control is simple, and all clauses have a declarative reading (due to the absence of free variables in the database set predicate and the result relation of the database evaluation being a set).

8.2.3 Interactive planning

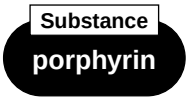
With a separate `select`/4 predicate synthesis planning can be made interactive: instead of having `member`/2 select a reaction or superclass relationship from the list of items retrieved from the database, the user is asked to select an item directly in the graphical representation of the synthesis tree.

The leaves of the current branch in the tree are the selectable items, and clicking on one of them leads to the next possible reaction steps being computed and displayed (Fig. 27.). Here `select`/4 is implemented as a mouse input predicate: Double-click on a leaf node in the tree expands (= selects for continuation) the node, a double-click inside the tree collapses (= aborts searching for further reactions) the subtree underneath the current node.

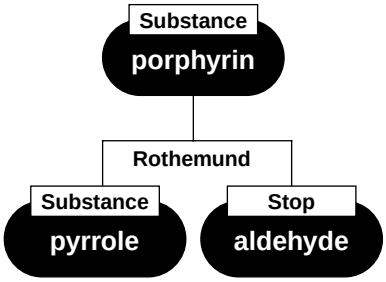
8.2.4 Adding higher-order control to the database access

`db_retrieve`/3 retrieves reactions and superclass relationships from the external database in the order determined by the arguments in the projection term. Hence, some higher-order control is exercised implicitly already, because the order in which data is retrieved is independent of any ordering in the relation tables.

In the current version of the algorithm, the projection term is coded into the program and hence cannot be changed. A dynamic formulation of the projection term is possible by having the user specify in which order database records are to be retrieved, and then use this specification to build

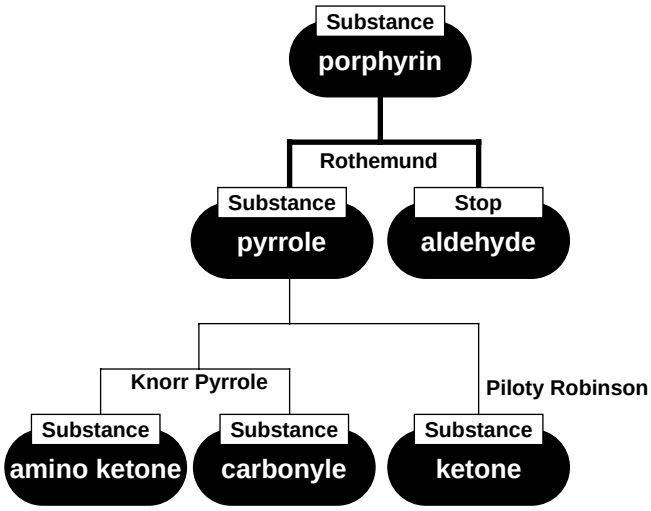


Double click on porphyrin leads to expanding the node.



Two leaves are selectable: pyrrole and aldehyde. Single click on aldehyde leads to the termination of the current branch at aldehyde. The leaf is marked with “Stop”.

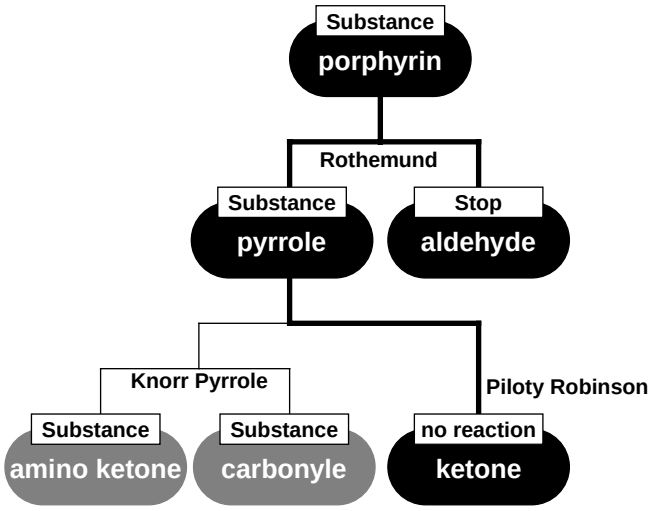
Double click on pyrrole leads to the expansion of the node.



The current branch through the synthesis tree is marked by thick lines.

Three nodes are selectable: amino ketone, carbonyle, and ketone. They belong to two different reactions.

Only one reaction can be chosen for continuing the planning. A double click in one of the substances will make all substances not belonging to that reaction unselectable. Hence, double click on ketone expands the ketone node, and shades all other nodes on the same level.



No reaction for ketone is stored in the database. The node is thus marked with “no reaction”.

One synthesis plan has been developed successfully. Further plans can be generated by closing the node ketone (double click on the node pyrrole inside the tree), and returning to the selection of nodes on the next higher level in the tree.

Fig. 27. Interactive synthesis planning for a porphyrin

the appropriate projection term. This can be done once prior to the execution of the program, or interactively, e.g. before accessing the external database.

In the following version of `db_retrieve`/3 the projection term is constructed dynamically (For the sake of clarity retrieving superclass relationships is omitted). This makes sense in the context of synthesis planning, because the synthesis tree is generally very shallow, and the criteria for choosing a reaction may be different in each step of the synthesis.

```
db_retrieve(Substance,Path,Tree):-
  build_access_term(ProjectionTerm,DatabaseGoal,ItemMask),
  db_access(ProjectionTerm,DatabaseGoal,ReactionsList),
  select(ReactionsList,ItemMask,Substance,Path,Tree).

select([],_,Substance,_,Substance).

select(ItemList,ItemMask,Substance,Path,Tree):-
  user_select(ItemList,SelectedItem),
  mask_attributes(SelectedItem,ItemMask,Item),
  synthesis(Item,Path,Tree).
```

Building the projection term dynamically poses two problems: the attributes which are needed for the evaluation to continue must always be included in the projection term, and those attributes which are not needed for the continuation must be masked. `build_access_term`/3 constructs the projection term, augments the database goal with existential quantifiers for those variables not included in the projection term, and returns a mask which permits the access to specified arguments only.

Example

In this example, additional name reaction information is stored in `reaction_information`/4.

```
% --- reaction_information(Name,Yield,Cost,References) --------
```

Suppose the user wants to retrieve reactions sorted by their cost. The projection term then is

```
(Cost, Name, Product, Educt),
```

and the database goal would be

```
Yield^References^(reaction(Product,Educt,Name),
  reaction_information(Name,Yield,Cost,References)).
```

The attributes necessary for the continuation are `Product`, `Educt` and `Name`, and hence the mask must be

```
(_, Name, Product, Educt).
```

If the user has selected a record, e.g. `(50,rothemund,porphyrin,pyrrole)`, from the list of database records, then the first argument is masked by `select`/5, and the last three are used to continue the evaluation in `synthesis`/3.

♦

Note that `build_access_term`/3 and `mask_attributes`/3 require extensive term manipulation. This term manipulation is possible entirely within Prolog.

8.2.5 Delegation of tests to the database system

In the introduction to section 8.2 I mentioned restricting the search space by explicitly requiring or disallowing specific substances or reactions in the synthesis tree. In the code fragments shown, only `legal_reaction`/2, which checks that there is no cycle in the reaction chain, can be found. Preventing specific reactions or substance classes from being used in a synthesis can be added easily: a list of reactions and substances which are not to be used is held in an extra argument. `legal_reaction`/2 is then extended to `legal_reaction`/3 and checks that no selected reaction or substance is on that list.

This immediately leads to the following remark: if a particular reaction or substance class is not to be used in the synthesis plan, why not prevent it from being retrieved from the database in the first place instead of doing that in Prolog? At least part — if not all — of the checking which is currently done by `legal_reaction`/3 should be delegated to the database system to reduce the number of database records retrieved.

The answer is that relational database languages are not powerful enough. Structured attributes, lists, or sets cannot be represented adequately in the relational database model if the 1. NF is to be respected. Thus everything that cannot be expressed in the database access language must be programmed and evaluated in Prolog. With more powerful database languages more work can be delegated to the database system. For example, with a HDBL [Pistor/Traunmüller 85] database system connected to Prolog, passing a list of values to the database system for the restriction of queries is possible because lists are primitive datastructures provided by HDBL.

8.3 Discussion

The application presented in this chapter is by no means trivial. Extensive rewriting of the original naive algorithm was necessary to reduce the number of database accesses, and to exploit the full capacities of database set predicates. Such rewriting is common practice when optimizing a given program.

Here, a clean distribution of control has been achieved by isolating database access in a single predicate and through the use of database set predicates. The resulting code is efficient without compromising too much on clarity.

In **DedChem**, the strategy for constructing a synthesis plan is different from the evaluation strategy of the underlying Prolog system. The Prolog evaluation strategy is depth first and left to right. The strategy for constructing plans is still depth first, but the user may select freely from the set of allowed next reactions and synonyms. This selection has distinct advantages: the number of possible next steps is known, and an optimized selection based on the comparison with alternatives is supported. Note that this selection from a set of items retrieved from the database is only possible

with database set predicates because of the set retrieval, the sorting of the result relation, and the dynamic datastructure used to hold the result relation.

The presentation of **DedChem** shows that a full-fledged programming language is needed to cover all relevant aspects of the application: user I/O, database access, and the application program itself. Prolog was designed to be a programming language, *with* I/O and system predicates etc. The Prolog programming environments available today feature comfortable interface libraries. There is thus no need to resort to other languages for implementing user-friendly interfaces. The same is true for database access: database set predicates can be implemented in Prolog, and they can be added to any existing Prolog system. Hence no other language is needed for accessing external databases.

Programming the application itself is facilitated by the high-level declarative language Prolog. Database set predicates embed database access into the logic programming language, and therefore, despite their being used as a means to increase efficiency, they contribute to programs which are easy to read and understand.

9

Outlook

Database set predicates are not restricted to accessing relational database systems. Access to more powerful database models, e.g. nested relations database systems, is also expressible.

9.1 Increasing the expressive power of the database access language

The relational database model requires the domains of its attributes to be atomic. This is a very severe restriction which makes using relational database systems almost impossible for a large class of practical applications.

Extensions to the relational database model have been proposed which feature a higher expressive power. A first extension is to allow attributes which are collections of atomic values, e.g. tuples, lists, or sets. A second extension are nested relations, i.e. relation tables the arguments of which may themselves be relations. Such extensions are known as NF^2 (non first normal form) databases.

NF^2 databases allow a more natural way of expressing data dependencies through a grouping of attributes, and they support efficient storage in that they express clustering conditions.

In contrast to the other approaches to coupled systems, database set predicates may access such higher database systems.

9.1.1 Tuple-, list-, and set-valued attributes

In this extension of the classical relational database model attributes may be collections of atomic values. The relational algebra and calculus were extended to set-valued attributes by [Özsoyoglu et al. 87]. Other collection constructors, such as tuples, or lists are easily incorporated.

- A *tuple attribute* consists of an n-ary term with a functor. Each argument of the term must be an atomic value.
- A *list attribute* consists of a list of finite length. This list contains only atomic values.
- A *set attribute* consists of a finite set of atomic values.

Constructor operators and operations to retrieve the individual values from such a collection can be defined in the logic language. Collections are commonly constructed by explicitly providing the elements that belong to the particular collection and unifying them with a logical variable, e.g.

Example

`Tuple = f(zurich,geneva)` for tuples
`List = [zurich,geneva,geneva]` for lists
`Set = {zurich,geneva}` for sets.

♦

The retrieval of individual elements is possible through pattern matching and unification for tuples, and a selection predicate for lists and sets.

Example

`Tuple = (Item1,Item2)` for tuples
`member(Item,List)` for lists
`element(Set,Element)` or `subset(Subset,Set)` for sets.

♦

For each of these operations an equivalent operation must be defined in the database system to be accessed. In fact, most commercial relational database system implementations provide such operations (which implies that the 1. NF may be violated in these systems). Typical examples are substring searches, which may be used to retrieve individual values stored in a string, or date arithmetic, which requires the separate treatment of days, months, and years.

Example

In the reactions database incompatibilities between name reactions and substance classes may be stored as an attribute of a name reaction, with incompatibilities a set of substance class names.

```
% --- reaction(Product, Educt, ReactionName, Incompatibilities) --
reaction(porphyrin, ketone, rothemund, {carbonyle, en, olefin}).
```

In a synthesis only such reactions may be used which are compatible with the substance classes in the current branch of the synthesis tree. In order to exclude incompatible substances as early as possible, the appropriate restriction is evaluated in the database system already:

```
?- ... /* Branch bound by previous goals */
  db_setof((Product,Educt,Name),
  (reaction(Product,Educt,Name,Incompatibilities),
   not subset(Incompatibilities,Branch)),List).
```

`subset`/2 is translated to the equivalent operation in the database system, and the query restriction is performed in the database system already.

♦

9.1.2 NF² databases

NF² databases, also called *nested relations*, extend the relational database model by allowing attributes to be relations themselves. A very concise definition is the one by S. Abiteboul [Abiteboul 90]: “In NF² databases, set and tuple constructors alternate”.

Extended relational algebras for NF² databases have been proposed [Jaeschke/Schek 82, Abiteboul/Bidoit 84]. Two restructuring operators are common to all these approaches:

- *nest*, written as ν, groups (or *partitions*) a relation into equivalence classes of attribute values. Two tuples are equivalent if they have the same values for the specified attributes. For each equivalence class a single tuple is placed into the result relation.
- *unnest*, written as μ, “flattens” a relation by concatenating every entry in the nested relation with the nesting attributes.

An extended relational calculus was developed by M. Roth [Roth 86] to compare the expressive power of extended algebras. It was shown that a relational calculus with an “element of” predicate and a means to access arguments in nested terms suffices to represent the operations of the extended algebras.

Single level nesting

The most common restriction in nested relations is to allow only one level of nesting because single level nesting can be expressed to some extent in standard SQL.

The GROUP BY construct essentially expresses the *nest* operator for a single level nesting. However, in current SQL database systems GROUP BY can only be used to retrieve such attributes for which there exists only one attribute value in a group. This effectively restricts GROUP BY to the computation of aggregate functions over the nested attributes because only such functions return a single value for the group of attributes.

The *unnest* operator cannot be expressed in standard SQL because this would require access to the internal structure of a relation-valued attribute.

Multi-level nesting

There have been various attempts to extend standard SQL to arbitrarily nested relations, i.e. nested relations with a depth of nesting ≥ 1.

SQL/NF [Roth 86] integrates nested relations into SQL by allowing relations to appear where in SQL only attributes could stand.

Example

The nested relation `flight` is defined as

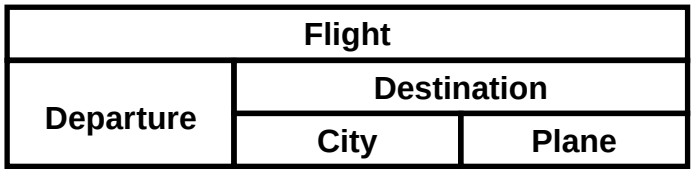


Fig. 28. Schema of the NF^2 table `flight`

"Retrieve all departures and their corresponding destinations" is expressed in SQL/NF as

```
SELECT departure,
         SELECT city
         FROM destination
FROM flight
```

The SELECT-part of the outer query contains a relation specification instead of an attribute name.

♦

Accessing NF^2 databases through database set predicates

Single-level nested relations can be accessed through database set predicates with a standard database goal which contains terms as arguments in subgoals. Multi-level nesting requires that database set predicates be nested, i.e. a database set predicate must appear in the database goal of another database set predicate.

The ν and μ operators are expressed through the quantification of variables in the database goal. ν is expressed by using free variables for those attributes which form the equivalence classes, and projection term variables for the other attributes; μ by including all variables of the database goal in the projection term.

Example

Single level nested relations can be accessed by database set predicates with standard database goals.

```
db_setof(City,
  Plane^flight(Departure,destination(City,Plane)),List)
```

retrieves a list of `Destinations` for every binding of `Departure`.

```
db_setof((Departure,City),
  Plane^flight(Departure,destination(City,Plane)),List)
```

retrieves a list of tuples `(Departure,Destination)`.

♦

In the examples above the *nest* operator was applied to relational database tables only. For the retrieval of data from NF^2 databases the predicate `element`/2, which selects an element from a set, must be used to select individual attribute values from nested relations.

Example

Retrieving the number of seats available for the individual flight connections is expressed as follows (with `plane`/2 a database predicate mapped to the relation table `Plane` with attributes `type` and `seats`):

```
db_setof((City,Seats),
  Destination^Plane^
  (flight(Departure,Destination),
   element(Destination,(City,Plane)),
   plane(Plane,Seats)),
  Result).
```

The projection term contains those variables corresponding to the attributes one is interested in, i.e. `destination` and `seats`. `flight`/2 in the database goal retrieves in its second argument the nested relation corresponding to the database attributes `departure` and `destination`. From this nested relation single tuples, represented through the term `(City,Plane)`, are selected through `element`/2. For each of these tuples a join over the attribute `plane` and `type` respectively is performed to retrieve the number of seats. This join is expressed through the shared variable `Plane` in `element`/2 and `plane`/2 respectively. The result relation is held in the variable `Result`.

The variable `Departure` is free, and hence the solutions to the database set predicate are distinct lists of instantiated terms for each binding of `Departure`.

♦

Translating NF^2 queries

The translation of database access requests to SQL/NF closely follows the procedure described in section 7.2. The free variables are translated to nesting attributes and thus the goals they occur in belong to the outer query. The other variables are translated to nested attributes and hence the goals without free variables form a query of their own in the SELECT-part of the outer query.

The translation to other database languages, such as HDBL [Pistor/Traunmüller 85], may be more difficult if these languages have constructs which cannot be represented directly in the logic language. For example, HDBL distinguishes between lists and sets. Prolog does not know sets, and hence they are represented as lists in most application programs. For a translation to HDBL it must be known which Prolog lists translate to HDBL lists, and which Prolog lists translate to HDBL sets. Additional information about the type of an attribute must thus be provided by the schema description. However, the translation procedure itself then is no longer independent of the database schema.

9.2 Updates through database set predicates

In the previous chapters, database set predicates have been restricted to read-only access to external databases. This restriction is due to their close relationship with the Prolog set predicates.

Prolog set predicates may be called with either the first two arguments, or with all three arguments instantiated. With the third argument a variable this variable is instantiated with the list of solutions to the goal argument. With the third argument bound to a list, the set predicates test whether the result of the all-solutions evaluation can be unified with this list. It is not possible, however, to evaluate set predicates “backwards”, i.e. to instantiate the template and the goal terms with solutions from the list argument.

In Prolog this restriction makes sense because running set predicates backwards implies that the instantiations of the goal argument be derivable from the list argument, and this is not guaranteed for arbitrary goal arguments since they may contain predicates which cannot be run backwards, e.g. control or system predicates, or predicates with side-effects. A second problem is that it may not be possible to determine the binding for every variable in the body of the rules called by the subgoal because they are not “visible”. This problem is known as the *view update problem* in the context of databases.

In database set predicates updates can be expressed either implicitly through “inverting” the proof procedure, or explicitly through update commands in the goal argument. In either case, the list argument of the database set predicate is fully instantiated, whereas the template and the goal argument are partially instantiated terms.

9.2.1 Implicit updates

Expressing updates implicitly amounts to inverting the proof procedure: instead of computing solutions from a given program, the program is constructed from the solutions supplied as input.

In database set predicates, the projection term and the database goal thus serve as program schemes which are materialized through the instantiations supplied by the list argument. This is possible provided that

- the database goal consists of a conjunction of positive base calls only, and that
- the arguments of the database goal are either constants, free variables which must be bound when the predicate is called, or variables which also occur in the projection term.

The semantics of updates through database set predicates requires the definition of the *scope* of update, and the *mode* of update.

The scope of update is determined by the free variables of the goal argument and is restricted to those tuples whose attribute values of the attributes corresponding to the free variables are equal to the instantiated free variables in the database goal. If there are no free variables in the goal argument, then the scope of update is the whole relation.

The mode of update is to replace these tuples by the ones supplied through the list argument of the database set predicate.

Example

The relation `Flight` contains the following records:

sw1	zurich	geneva	a-320
sw2	zurich	paris	a-320
sw3	paris	london	a-320

In this relation, the flights leaving Zurich are to be updated through the following command:

```
?- db_setof((No,Destination,Plane),
   flight(No,Departure,Destination,Plane),[(sw1,geneva,b-727)]).
```

with the free variable `Departure` bound to `zurich` when the predicate is called implicitly updates the base table `Flight` (with `Departure` uninstantiated, the update would be forbidden because of the missing value for the attribute `departure` in relation `Flight`).

The scope of update is restricted to those tuples in the relation `Flight` that have the value `zurich` in the attribute `departure`. These are replaced by the single record `(sw1,zurich,geneva,b-727)` which is a materialization of the database goal

```
flight(No,Departure,Destination,Plane)
```

and the projection term

```
(No,Destination,Plane)
```

The result relation then is

sw1	zurich	geneva	b-727
sw3	paris	london	a-320

Note that the other tuples remain unchanged.

♦

Implicit updates are a natural extension of database set predicates. However, for practical applications the update requests are too terse to be understood easily, especially if the goal argument consists of conjunctions of base calls.

Example

The implicit update formulated as

```
?- db_setof((No,Destination,Plane,Seats),
 (flight(No,Departure,Destination,Plane),plane(Plane,Seats)),
 [(sw1,zurich,geneva,b-727,150)]).
```

with `Departure` bound to `zurich` will replace the records in relation `Flight` with the value of the attribute `departure` equal to `zurich` by the record `(sw1,zurich,geneva,b-727)`, and it will replace all records of the relation `Plane` by the one record `(b-727,150)` because the update in `Plane` is not restricted by a free variable.

♦

Implicit updates face another problem: Often there is no direct translation of implicit database updates to a database language. For example, there is no command in SQL to express the replace mode of update, and hence replacing tuples in the database has to be implemented through a delete

command with a search condition, and a subsequent insertion of the values supplied through the list argument of the database set predicate.

9.2.2 Explicit updates

With explicit updates, the database access language is extended through either

- a new database set predicate, or
- database update commands in the goal argument.

In the first case, the database set predicate `db_update`/3 is introduced. The arguments of `db_update`/3 are the same as in the other database set predicates, and the operational semantics is that of the implicit update described above.

Introducing a new database set predicate for updates would allow the other database set predicates to retain their operational semantics even with the third argument instantiated, and it would make updates to the database explicit without any dependency on the underlying database manipulation language.

In the second case update commands are included in the goal argument of database set predicates as the reserved predicates `replace`/1, `delete`/1, and `insert`/1 which take as argument a base call.

Example

```
?- db_setof((No,Destination,Plane),
insert(flight(No,Departure,Destination,Plane)),[(sw1,geneva,b-
727)]).
```

with `Departure` bound to `zurich` will insert into the relation `FLIGHT` the record `(sw1,zurich,geneva,b-727)` to the previous entries in the relation table.

♦

Generally, these reserved predicate names are chosen to reflect the commands of the underlying database manipulation language. However, this makes visible the underlying database manipulation language and hence violates the principle of embedding. Furthermore, the burden of choosing the appropriate method for database updates is placed on the application programmer.

9.2.3 Summary

It must be noted that the problem of integrating updates into logic programs has not yet been solved satisfactorily. From a theoretic point of view, updates to the database are an extension of the set of axioms of the logic theory. Augmenting the set of axioms entails non-monotonicity: theorems can now be proved that could not be proved before.

In logic programming, updating the set of axioms is achieved through side-effects which implies a permanent change of the program code. Backtracking at later stages does not undo the program

code modification, so that although the original goal failed, the set of axioms is changed. A solution may be the approach taken in Gödel where the current database is passed on as a context argument during the evaluation. Database updates lead to the definition of a new context for subsequent goals. Upon failure, any database update is undone, and the proof continues with the previous database context [Hill/Lloyd 91]. Database set predicates also have a natural update semantics in that any backtracking is performed on the list datastructure that holds the result relation read in when the goal was called for the first time — subsequent database updates have no effects on this list. This semantics follows the defensible semantics for assert and retract as proposed by Lindholm and O'Keefe [Lindholm/O'Keefe 87].

In the context of physically loosely coupled systems the update problem is particularly acute because with multi-user access updates to the database may occur which cannot be controlled by the current application program and hence may lead to unpredictable results. However, this problem pertains to multi-user database systems in general, and suitable mechanisms such as locking must be applied.

In practice, the introduction of a specific database set predicate for updates is a reasonable way of integrating updates into logic programming languages, because it distinguishes database updates from data retrieval in the program code, but does not require a separate database access language. Furthermore, the translation procedure, which is different for retrieval and update, is determined explicitly by the predicate name, and not implicitly through the instantiation pattern of the arguments.

10

Conclusion

Database set predicates embed access to external databases into logic programming languages based on SLDNF resolution. This embedding is achieved through a physically loose and logically tight coupling of the logic programming language and the database system.

On the physical level, the database evaluation is embedded into the logic language evaluation by confining access to and retrieval from the external database to the standard set-oriented data manipulation language interface of the database system. In previous approaches to physically loosely coupled systems the external database is accessed via the procedural programming language interface of the database system one record at a time to match the tuple-oriented evaluation strategy of the logic programming language.

On the logical level, access to the database is embedded into the logic programming language through the powerful term and list datastructure primitives provided by the logic programming language which allow the adequate representation of any database query and its corresponding result relation. In previous approaches to logically tightly coupled systems in which the logic programming language is the sole language, this language is restricted in its expressive power to Datalog with negation and arithmetics, and the database itself must respect the *allowedness* constraints on the form of its predicates.

The high expressive power of the database access language of database set predicates stems from the ability to discern variable quantifications, and the independence of the projection term and the database goal. This expressive power contributes to efficiency through maximally restrictive queries, it permits exploiting the full capabilities of external database systems, including the computation of aggregate functions and the expression of higher order control such as grouping and sorting, and it supports access to higher database systems, such as databases with non-atomic attributes or even NF^2 databases.

Database set predicates can be implemented on top of most commercial Prolog systems in Prolog itself. In fact, writing an efficient compiler to translate database access requests to a database query

is a straightforward task in the high level declarative language Prolog. For the communication between the logic programming language system and the database system all that is required are low level stream I/O predicates for inter-process communication, or a foreign language interface for communication through procedure calls. Both mechanisms are supported in most commercial Prolog environments.

Database set predicates have two distinct advantages for practical applications. They support a declarative style of programming without compromising on efficiency, and their inherent independence of a particular database system implementation allows accessing a multitude of different database systems. The importance of this last feature for high level applications, e.g. knowledge base and/or expert system applications, cannot be overestimated.

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