An algebraic specification of the relational database language SQL

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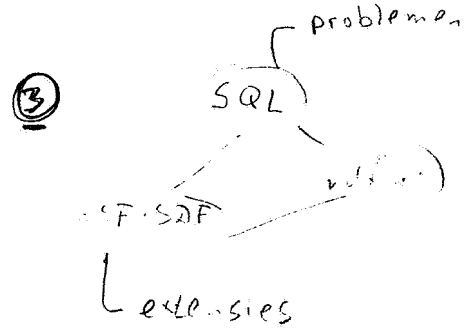

1 Introduction

The subject of this masters thesis is an algebraic specification of the database language SQL.

When faced with the problem of defining a formal (programming) language, we have to investigate the following aspects of this language:
- its concrete (i.e., lexical and context-free) syntax,
- its static semantics, and
- its dynamic semantics.

The first of these topics, the syntax of a language, is usually specified using a context free grammar, like BNF. This describes exactly which clauses belong to the language; all other sentences should be rejected. Low level syntax such as which character set to use, the notion of newline, and definition of layout and comment is given apart from the BNF and specified in natural language.

The next aspect, the static semantics of a language, is meant to define further constraints on the language. A large part of these constraints have normally to do with declarations of objects in the language (variables or routines; identifiers in general) and of their correct use. Especially the declared type of an object is important, therefore checking the static semantics of a given language clause is usually called typechecking and we will use this term throughout the rest of this document. Typechecking rules are written down in a far less formal way than was possible with the syntax. Natural language is usually the appropriate medium.

Finally, the dynamic semantics of a language describes what a given sentence in the language means exactly. Having defined the objects that can be manipulated by the language, the meaning of a clause can be depicted in terms of these objects. The semantics of Pascal, for example, deals with objects like numbers, strings, arrays, records and files. The meaning of a query in a database language SQL will be explained in terms of derived data from databases.

Of these three aspects of a language definition, only the least difficult one is clearly specified using a formal method, the others (including the definition of objects) are usually specified in natural language and are evidently defined less precise.

In this thesis we will investigate if it is practically possible, and if so to which extend, to use a formal method in order to specify syntax, typechecking rules and semantics of the language SQL. SQL is a data definition and manipulation language based on relational databases and has been chosen for a number of reasons:
- SQL is not a traditional programming language, as for example Pascal would have been,
- the language has been defined in an international standard [1] using syntax, syntax rules and general rules, in the way we described above,
- the objects to be defined and manipulated using the language, relational databases, have a clear algebraic notion, and
- many complain that SQL is still incomprehensive in many ways.

The system we used for specifying SQL and its underlying relational databases is the ASF+SDF system [2], which is a environment for the interactive development and implementation of languages. ASF+SDF has been developed in the GIPE project (Generation of Interactive Programming Environments - ESPRIT Project 348).

Provided a (modular) syntax definition of a language, the ASF+SDF system generates interactively a parser and a generic text and structure editor (called GSE) for that language [3]. It then allows to enter some term, which is a sentence in the specified language, and have it parsed on demand of a mouseclick. After the term is parsed without errors, the editor then places its focus on the smallest syntax construction where the mouseclick took place and we are able to inspect the structure of our language definition by moving the focus around.
Changing the syntax definition of the language results in an incrementally changed parser and generated editor, so this system is extremely suitable for developing a language definition interactively.

From a given parse tree the ASF+SDF system also creates an abstract syntax tree, which is used to match with a set of conditional equations. These equations are given in the equations section of a module and form the definition of a term rewriting system with which we can reduce a given term in the language to its normal form. In this way we can, for instance, define how to evaluate an expression, execute a statement or calculate the result of a typecheck function.

In section 2.3 we will present a more elaborate description of the ASF+SDF system, including an example.

The remainder of this paper is organized as follows:

In chapter 2 we present some formal background concerning relational databases, the language SQL and the ASF+SDF formalism.

A specification of a relational database system (RDBS), based on the relational algebra, is given in chapter 3. First, a sample database with some queries is shown to illustrate the kind of system we want. Next, the structure of the syntax modules and each module in turn is described and finally, we return to the sample database to show that we can actually calculate the given queries.

In chapter 4 we deal with the syntax of SQL. First, we describe the conversion of the BNF definition from the standard to an SDF syntax definition. Then, after discussing some design choices, the implementation of a typecheck function for SQL schema's and query specifications is described.

Chapter 5 deals with the semantics of a small but important subset of SQL. This is done by showing specifications of translation functions from SQL language clauses to the RDBS language.

In chapter 6 we reach some conclusions with respect to the objects we had in mind.

Some comments about the practical sides of working with the ASF+SDF formalism and -system are given in chapter 7.

The appendices list the BNF grammar of SQL and all ASF+SDF modules.

2 Formal background

2.1 Relational Algebra, Relational Databases

In this paragraph we present some formal background concerning relations, relational databases and relational algebra in the form of definitions and related issues:

Relations

Let $D_1, D_2, ..., D_n$ be a collection of not necessarily different (finite) sets. Then we can define the product $D_1 \times D_2 \times ... \times D_n$ as the collection of all possible n-tuples $<d_1, d_2, ..., d_n>$ such that d_i is an element of D_i ($i = 1..n$).
R is called a relation over $D_1 \times D_2 \times ... \times D_n$ when R is a subset of $D_1 \times D_2 \times ... \times D_n$.
$D_1, D_2, ..., D_n$ are called the domains of R; $d_1, d_2, ..., d_n$ are the attributes of R.
The degree of R is the number of R's attributes (n in this case); the cardinality of R is the number of elements (tuples) in R.
A value of R is a value of an attribute of some tuple in R.

Example 1
Domains
Let Booleans, Integers, Reals and Strings be domains for objects like true, 147, 199.95 and 'Sunday' respectively.

Relations

Students $\subseteq$ Integers $\times$ Strings $\times$ Strings -- i.e. student number, name and phone

Members $\subseteq$ Integers $\times$ Strings -- i.e. student number and sport

Contributions $\subseteq$ Strings $\times$ Reals -- i.e. sports and price

Instances

```
Students = {
      < 891247 , 'Al-Hassan', '02990 - 42185' >
      < 893218 , 'Bakker', '020 - 6123316' > ,
      < 896673 , 'Jansen', '020 - 6123316' >,
      < 901274 , 'The', '> }
Members = {
      < 891247 , 'Tennis' >,
      < 893218 , 'Zwemmen' >,
      < 893218 , 'Tennis' > }
Contributions = {
      < 'Zwemmen' , 50.00 >,
      < 'Tennis', 75.00 >,
      <'Wandelen', 1.50 > }
```

X

Relational databases

A relational schema is a set of rules which give a description of the defined domains, relations over these domains, and names and domains of attributes, possibly completed with additional constraints on allowed values.
A relational database is an instance of a relational schema.

Example 2
Domains
-- Booleans, Integers, Reals, Strings: predefined

Sports = { 'Zwemmen', 'Tennis', 'Wandelen', 'Voetbal' }
Numbers = { n ∈ Integers | (n ≥ 800000) ∧ (n ≤ 919999)}
-- Note: the first two digits of these numbers represent the year of arrival.

Relations
Students(S_number: Numbers, name: Strings, phone: Strings)
Key: S_number
Members(M_number: Numbers, M_sport: Sports)
Key: M_number + M_sport
∀ M_number ∈ Members ∃ S_number ∈ Students : M_number = S_number
Contributions(C_sport: Sports, amount: Reals)
Key: C_sport

-- Note: "Key" is a constraint indicating that any occurrence of a value of a key attribute, or combination of attributes, may not occur more than once in the relation.
X

Issues related to relational databases

- A relation is an unordered set:
  There is no ordering defined on the domains (which are sets), so there is also no ordering defined on tuples derived from those domains. In practice however it is often convenient to have such an ordering, especially for (sorted) listings or other presentations of data.

- Attributes are ordered:
  We cannot reorder the attributes of a tuple at will without loss of meaning, so we have to number these attributes (first, second, ...). This numbering will in most cases be transparent because of the use of attribute names as given in the relational schema.

- Relations are not supersets:
  Every tuple from a relation must have a unique appearance in that relation, otherwise a relation should have been defined as a superset. If one demands us to have unique tuples, one apparently assumes implicit that e.g. {a,a} ≠ {a}. For several database queries, determining the cardinality of a relation for instance, it is necessary that duplicate tuples are not removed automatically.

- The key of a relation:
  The key of a relation is defined as a combination of some or all attributes of a tuple. The values of these attributes must appear unique within the relation. Therefore an instance of a key is consequently an identification of exactly one tuple (or no tuple at all).

- Constraints upon relations:
  We can restrict the appearance of certain tuples of all possible tuples over $D_1 \times D_2 \times ... \times D_n$ by specifying field-, intrarecord-, and interrecord constraints. A key of a relation is one form of such constraint.

- Null-values:
  Each domain can be extended with a omni-typed value *null*, which stands for unknown, unavailable, etc. Special logic has to be defined when dealing with the null-value.

- Normalisation:
  A relation R is in first normal form, 1NF, when every value of R is nondecomposable (atomic). There are several normal forms defined on relations, each next normal form will rule out some sort of so called anomalies.
  Claim: every relation can be brought to 1NF because of the associativity of ×:
  $D_1 \times (D_2 \times D3) = (D_1 \times D_2) \times D_3 = D_1 \times D_2 \times D_3$ etc.

Relational algebra

When R, R_1, R_2 .. R_n are themselves relations, then so are the results of the following expressions:

- $R_1 + R_2$ union
- $R_1 * R_2$ intersection
- $R_1 - R_2$ difference
- R_1 / R_2 division
- $R_1 \# R_2$ product
- (R) brackets
- R | $p(a_1, a_2, ..., a_n)$ selection; p is a predicate over attribute names of R
- R[$b_1, b_2, ..., b_m$] projection; b_i is an attribute name of R
- $R_1 \# R_2 \# ... \# R_X$ | $p(a_1, a_2, ..., a_y)$ [$b_1, b_2, ..., b_z$] join

Some of these operations on relations are well-known from the set theory; these are union (normally $A \cup B$), intersection (normally $A \cap B$), difference (normally also A - B) and Cartesian product (normally $A \times B$). Rather unknown is division: A/B is the set values x such that the pair <x,y> appears in A for all values y appearing in B. Bracketing is used for grouping sub-expressions.

Typical relational operators are selection, projection and join:

Selection is used for selecting a (possibly empty) subset of R such that for all tuples of the subset the predicate p holds (and for all tuples which are not selected, the predicate p does not hold). The predicate p is taken over the attributes of R, but may also involve other relations as well (then it's a so-called *outer-reference*).

Example 3
The selection "Students | S_number < 900000" will list all students (i.e. their number, name and phone) who arrived before 1990. (Remember that the first two digits of the number represent the year of arrival.)
X

Example 4
The selection "Students | S_number ∈ (Members | M_number = S_number)" asks for students for who's student-number occurs in Members, i.e. a listing of all students who are enlisted for some sport.
X

Projection is used for selecting some of the possible attributes resulting from a relation (expression), possibly rearranging the selected attributes.

Example 5
The projection "Students[phone, name]" will list students phone and name.
X

Two points of interest arrive here:

1. duplicate tuples can be introduced by union, but occur more frequently (and more unexpected) in the result of a projection. As an example: "Which students are sports(wo)men?" can be asked as: "Members[M_number]", which results in 4 student-numbers in Example 1, when there is no automatic removal of duplicate tuples and

2. the projection can also serve as a *value-selector*: not only the needed attributes are listed, but expressions involving those attributes.

The next example will illustrates this last point.

Example 6:
The projection "Employee[surname + lastname, 'will get $', salary * 1.05]" will give a listing:
Jan Jaap de Slome will get $105
instead of something less informative like:
'Slome' 'Jan Jaap de' 100
which will be the result of "Employee[lastname, surname, salary]"
[X]

Join is the most important of the relational operators. It is however not a operator on its own, but a combination of product, selection, and projection.

Example 7
The query "(Students # Members | S_number = M_number)[name, sport]" lists student names who practice at least one sport, together with the sport they practice.
[X]

This is the most general form of join; most frequently found is the so-called natural join, which is a combination of two relations sharing the same attribute, and removal of one of these duplicate attributes, as in "Join(Students, Members, S_number, M_number)[name, phone]".

Issues related to the relational algebra

- Union-compatibility:
  In order to perform "+", "*" and "-" it is necessary that the corresponding attributes of the operands are drawn from a common domain.

- Attribute names of a result:
  The product (join) of two different relations can result in attributes with the same name. Sometimes even a product of the same relation is wanted and all attribute names will occur twice in the result. In such a case, a mechanism for renaming of the attributes is necessary, either by naming the relations involved (as in "Students.name") or by giving an alias to relation names. In most database systems some ad-hoc mechanism is chosen.

- Priorities and associativity of operators:
  The operators "+", "*" and "#" are associative, "-" and "/" are not associative. Concerning priorities there is a preference towards the ordering: "#" > "*", "/" > "+", "-". Then, "A # B * C + D" will be interpreted as "((A # B) * C) + D". We are not convinced that this is the right ordering.

- Views on relations and databases:
  One mechanism for offering the several users of a database system a different look at the information, is by defining views. This is done by declaring a view name and an associated query (i.e. a relational expression) over other relations and views. If someone is interested in a list of names of all student swimmers for example, one can declare the view:
  Swimmers = (Students # Members | (S_number = M_number) & (sport = 'Zwemmen'))[S_name]
  If, for instance, a new enrollment is made for a student in the relation Members, the view will automatically be updated when his or her sport is 'Zwemmen'.

- Cursors (tuple variables for use in relational calculus):
  For procedures on relations, that cannot be done using the relational operations only, one can declare a cursor, which is a variable ranging over all tuples of a relation. All relational operators are effectively implemented by using some sort of (implicit) cursor; this however may not be visible to the user. Therefore some propose that the relational calculus (i.e. a calculus for relations with operations expressed in terms of cursor movements and assignments) is a good alternative for the relational algebra. It has been shown that both algebra and calculus can express exactly the same, so they can be considered equally powerful.

2.2 Database language SQL

The name SQL stands for Structured Query Language, and was designed in the mid and late 1970s by IBM, based on their System R technology. SQL has facilities for defining, manipulating, and controlling data in a relational database. There are numerous commercially SQL-based products; the two most important are ORACLE by Oracle Corporation and SQL/DS by IBM. In 1986 SQL became an official international standard by ANSI and ISO.

The complete definition of the SQL standard is written in the Final draft ISO 9075-1987(E) Database Language SQL (Nov. 1986) [1]. Except for some preliminary overview and concepts, this definition is given by specifying the several syntactic elements of SQL, in terms of:
- Function: a short statement of the purpose of the element,
- Format: an extended BNF definition of the syntax of the element,
- Syntax Rules: additional syntactic constraints that the element shall satisfy, and
- General Rules: a specification of the run-time effect of the element.

The BNF definition of SQL is listed in Appendix A for reference and has the following extensions to standard BNF notations:
- [] optional element
- ... elements repeated one or more times
- { } grouping of sequences of elements

A short abbreviated definition of <schema> (§6) and <query specification> (§5), together with some explanation will be presented hereafter. Our extensions to standard BNF are:
- Item* zero or more repetitions of Item
- Item+ one or more repetitions of Item
- {Item ","}* list of zero or more Items, separated by ","
- {Item ","}+ list of one or more Items, separated by ","
- [Item] optional Item
- (Item) grouping of Item

A relational schema is defined in SQL as:

```
Environment ::=
  CREATE ENVIRONMENT Ident Schema*

Schema ::=
  CREATE SCHEMA AUTHORIZATION Ident SchemaElement+

SchemaElement ::=
  CREATE TABLE TableName "(" {(ColumnDef | TableConstraint)","}+ ")"
| CREATE VIEW TableName ["(" {Ident ","}+ ")"]
  AS QuerySpec [WITH CHECK OPTION]
| GRANT (ALL PRIVILEGES | {Action ","}+) ON TableName
  TO {(PUBLIC | Ident) ","}+ [WITH CHECK OPTION]

TableName ::= [Ident "."] Ident

TableConstraint ::=
  (UNIQUE | PRIMARY KEY) "(" {Ident ","}+ ")"
| FOREIGN KEY "(" {Ident ","}+ ")"
|  REFERENCES TableName ["(" {Ident ","}+ ")"]
|  CHECK "(" SearchCondition ")"

Action ::=
  SELECT
| INSERT
| DELETE
```

```
| UPDATE ["(" {Ident ","}+ ")"]
| REFERENCES ["(" {Ident ","}+ ")"]
```

An environment is not part of the SQL language, but an 'implementor-defined concept' as defined in §6.1 <schema> Syntax Rules 1. A schema lists an authorization identifier and one or more table-, view- or privilege definitions.

A table definition (CREATE TABLE ...) defines a table (i.e. a relation in first normal form) with columns (attributes) defined in the column definitions. Since two tables in different schemas can have the same name, such a table name may be preceded by the identifier of the enclosing schema, as in "SCHEMA_IDENT.TABLE_IDENT". Table constraints define the constraining of allowed rows (tuples) to be inserted in a table.

A view definition (CREATE VIEW ...) is the method to create a specific look at the data, as has been discussed in the introduction. It defines the name of the view, an optional list of column names (a view can be seen as a table with rows too) and a query resulting in the desired data.

Operations requested by a user of the database can be limited by the creator of the database by (not) giving allowance to specific users to perform certain operations (called privileges) on a defined table . This is done using a privilege definition (GRANT ...).

```
ColumnDef ::=
  Ident DataType [DEFAULT (Literal | USER | NULL)] ColumnConstraint*

DataType ::=
  CHARACTER ["(" Unsigned ")"]
| CHAR      ["(" Unsigned ")"]
| (NUMERIC | DECIMAL | DEC) ["(" Unsigned ["," Unsigned] ")"]
| INTEGER
| INT
| SMALLINT
| FLOAT ["(" Unsigned ")"]
| REAL
| DOUBLE PRECISION

ColumnConstraint ::=
  NOT NULL [UNIQUE | PRIMARY KEY]
| REFERENCES TableName
| CHECK "("-SearchCondition ")"
```

A column definition is specified as an identifier (attribute name), a datatype (only a limited set of datatypes exist in SQL and there is no mechanism to define further domains), an optional default (i.e. a value to be inserted when no specific value is given) and a set of constraints on the allowed values of the column.

Example 8

```
CREATE SCHEMA AUTHORIZATION ADMINISTRATION
  CREATE TABLE SPORTS (
    SPORT    CHAR(15)
  )
  CREATE TABLE STUDENTS (
    NUMBER   NUMERIC(6)
    NAME     CHAR(25)
    PHONE    CHAR(15)
  )
  CREATE TABLE MEMBERS (
    NUMBER   NUMERIC(6)
    SPORT    CHAR(15)
```

```
  )
  CREATE TABLE CONTRIBUTIONS (
    SPORT    CHAR(15)
    AMOUNT   NUMERIC(3,2)
  )
X
```

The most important information retrieval function in SQL is a query specification (query for short). Query specifications occur in many places in SQL, but their most common use is an interactive query typed by a user of the database.

```
QuerySpec ::=
  SELECT [ALL | DISTINCT] ("*" | {ValueExpr ","}+)
  FROM { (TableName [Ident]) ","}+
  [WHERE SearchCondition]
  [GROUP BY { (ColumnSpec) ","}+]
  [HAVING SearchCondition]

ColumnSpec ::=
  [TableName "."] Ident

SearchCondition ::=
  SearchCondition AND SearchCondition
| SearchCondition OR SearchCondition
| NOT SearchCondition
| Predicate
| "(" SearchCondition ")"

Predicate ::=
  ValueExpr ("="|"<>"|"<"|">"|"<="|">=") (ValueExpr | SubQuery)
| ValueExpr [NOT] BETWEEN ValueExpr AND ValueExpr
| ValueExpr [NOT] IN (SubQuery | {ValueSpec ","}+)
| ColumnSpec [NOT] LIKE ValueSpec [ESCAPE ValueSpec]
| ColumnSpec IS [NOT] NULL
| ValueExpr ("="|"<>"|"<"|">"|"<="|">=") (ALL | SOME | ANY) SubQuery
| EXISTS SubQuery

SubQuery ::=
  "(" SELECT [ALL | DISTINCT] ("*" | ValueExpr)
  FROM { (TableName [Ident]) ","}+
  [WHERE SearchCondition]
  [GROUP BY { (TableName) ","}+]
  [HAVING SearchCondition]
```

A query specification has in general the following outline:

SELECT V1, V2, ..., Vn
FROM T1, T2, ..., Tm
WHERE SearchCondition
GROUP BY C1, C2, ..., Cx
HAVING SearchCondition

It combines Cartesian Product (FROM T1, T2, ...), selection (WHERE SearchCondition) and extended projection (SELECT V1, V2, ...).
A query without projection is written down as "SELECT * FROM ... WHERE ...".
The result of a query can be explained as follows:

1. The Cartesian Product of all tables mentioned in "FROM T1, T2, ..., Tm" is calculated.
(As with the definition of tables in a schema, the name of a table may be qualified with the corresponding authorization identifier of the schema. In case of ambiguous table names this qualifier is mandatory. Other ambiguities, e.g. when a product of a table with itself is required, are resolved by specifying a correlation name, i.e. an additional identifier after the table name.)

2. Each row of this product is inspected with respect to the optional search condition. This is a boolean condition built out of basic predicates involving some or all attributes of the row. The result consists of all rows for which this search condition holds.

3. The former result is rearranged to form groups with equal values for the columns mentioned in the optional GROUP BY clause.
(A column is referenced using a single identifier, the column name. In case of ambiguity it is preceded with the name of a table, which can be an original table name or a correlation name.)

4. Each resulting group is in turn tested against the search condition of an optional HAVING clause. The result is formed out of all groups for which this condition holds.

5. The result of 1-4 is further processed by the select list "V1, V2, ..., Vn".
"SELECT *" yields all attributes just as they are. "SELECT V1, V2, ..., Vn" results in a table with degree n, each attribute value calculated from the value expressions V1..Vn (see below).
The keyword DISTINCT will remove all duplicate tuples in the final result.

Example 9
Select candidates for the swimming competition...:

```
SELECT NAME, PHONE
FROM STUDENTS, MEMBERS
WHERE (STUDENTS.NUMBER = MEMBERS.NUMBER)
  AND (SPORT = 'Zwemmen')
```

X

Example 10
Print student names which are enrolled for more than one sport...:

```
SELECT NAME
FROM STUDENTS, MEMBERS
WHERE STUDENTS.NUMBER = MEMBERS.NUMBER
GROUP BY NAME
HAVING COUNT(SPORT) > 1
```

X

The possible predicates in a search condition are briefly illustrated with the following examples.
(Note: many predicates allow an optional NOT to be specified, the result of the predicate is negated then.)

Examples 11
• value comparison:

```
SELECT * FROM STUDENTS WHERE STUDENTS.NUMBER = 901274
```

(Possible comparisons are also <>, <, >, <=, and >=. A subquery is allowed on the right hand side of the comparison, it should then result in a single value.)

• value within a range of values:

```
SELECT * FROM STUDENTS WHERE NUMBER BETWEEN 900000 AND 909999
```

(i.e. 900000 <= NUMBER <= 909999)

• value occurrence in a set of values:

```
SELECT NUMBER FROM MEMBERS WHERE SPORT IN 'Tennis', 'Voetbal'
```

(Here too a subquery is allowed on the right hand side, in this case it should result in a single column.)

• synonym comparison: (all names beginning with letter C)

```
SELECT NAME FROM STUDENTS WHERE NAME LIKE 'C%'
```

• test if column has the null value:

```
SELECT SPORTS FROM CONTRIBUTIONS WHERE AMOUNT IS NULL
```

• universal quantifier: (select oldest students)

```
SELECT * FROM STUDENTS
WHERE NUMBER <= ALL (SELECT NUMBER FROM STUDENTS)
```

• existence quantifier: (select non-sports(wo)men)

```
SELECT * FROM STUDENTS
WHERE NUMBER <> ANY (SELECT NUMBER FROM MEMBERS)
```

(SOME and ANY are identical)

• existence (also illustration of outer reference and of use of a correlation name):

```
SELECT NAME FROM STUDENTS
WHERE EXISTS
     (SELECT NUMBER FROM MEMBERS SPORTERS
      WHERE STUDENTS.NUMBER = SPORTERS.NUMBER)
```

X

Value expressions are common expressions resulting in a single value, as opposed to table expressions resulting in tables. These expressions are composed of literal values (string, numeric, or the special keyword USER), references (to columns, parameters, or variables), and results of functions. They are bound together with operators "+", "-", "*", and "/". The associativity- and priority properties of the operators are forced by the original BNF definition and are not visible here.

```
ValueExpr ::=
  ValueExpr "+" ValueExpr
| ValueExpr "-" ValueExpr
| ValueExpr "*" ValueExpr
| ValueExpr "/" ValueExpr
| "+" ValueExpr
| "-" ValueExpr
| ValueSpec
| ColumnSpec
| SetFuncSpec
| "(" ValueExpr ")"

ValueSpec ::=
  Ident [[INDICATOR] Ident]                -- parameter
| ":" Ident [[INDICATOR] ":" Ident]        -- variable
| Literal

Literal +:=
  "'" ~['']* "'"                           -- string
| ["+"|"-"] Unsigned                       -- exact
| ["+"|"-"] Unsigned "."                   -- exact
| ["+"|"-"] Unsigned "." Unsigned          -- exact
| Exact "E" ["+"|"-"] Unsigned             -- approx
| USER

SetFuncSpec ::=
```

```
   COUNT "(" "*" ")"
 | (AVG | MAX | MIN | SUM | COUNT) "(" DISTINCT ColumnSpec ")"
 | (AVG | MAX | MIN | SUM) "(" [ALL] ValueExpr ")"
```

Using the built-in functions one can count the number of rows, sum the values of a column, or determine the minimum, maximum, or average of a column.

Examples 12

• determine the number of students:

```
SELECT COUNT(*) FROM STUDENTS
```

• find oldest student number:

```
SELECT MIN(NUMBER) FROM STUDENTS
```

• find the name of oldest students:

```
SELECT NAME FROM STUDENTS WHERE NUMBER = MIN(NUMBER)
```

X

With the exception of GROUP BY, built-in functions cannot be intermixed with attribute names;

```
  SELECT NAME, COUNT(*) FROM STUDENTS
```

, for instance, is not allowed.

2.3 The ASF+SDF formalism

In this section we will demonstrate the practical use of the ASF+SDF formalism. For a more formal description, see [2]. Theoretical background about algebraic specifications and term rewriting systems can be found in [4].
So without going into much detail, we will explain the modular structure of ASF+SDF specifications, the various sections they consist of, and the parsing and reduction of terms.

An ASF+SDF specification is composed of a number of modules in which we define the syntax of a language. Such a syntax definition consists of sort names, lexical syntax, and context-free syntax and can either be exported (i.e. visible to the outside world) or hidden. Modules can import other modules and so use their exported syntax. The modules of a specification are bound together by such import relations. Next, we show two modules forming the specification of the boolean datatype. The first module, Layout, does not import any other modules, but is instead a basic module to define the predefined sort LAYOUT. This definition of blank space or comment is used by the scanner to skip when such phrases are encountered in the input.

```
module Layout
exports
  lexical syntax
    [ \t\n]                -> LAYOUT
    "%%" ~[\n]* [\n]       -> LAYOUT
end Layout
```

The first definition specifies layout to be a space character, a tab or the newline character; the brackets around them indicate a set of possible characters. The second definition tells us that everything between two percent signs and the newline should also be treated as blank space, so this is our definition of comment. (Note: the phrases "module Layout" and "end Layout" are not part of the ASF+SDF implementation, but included here for readability.)

Our next module, Booleans, first imports module Layout we defined just before and then defines the datatype booleans with sortname BOOL. Booleans can have values "true" or false" and can be manipulated with operators "not", "or" and "and".

```
module Booleans
imports
  Layout
exports
  sorts
    BOOL
  lexical syntax
    "true"                -> BOOL
    "false"               -> BOOL
  context-free syntax
    not BOOL              -> BOOL
    BOOL or BOOL          -> BOOL { left }
    BOOL and BOOL         -> BOOL { left }
    "(" BOOL ")"          -> BOOL { bracket }
  variables
    "bool" [0-9']*        -> BOOL
priorities
    not BOOL -> BOOL >
    { left: BOOL and BOOL -> BOOL, BOOL or BOOL -> BOOL }
equations
  [not1]  not true  = false
  [not2]  not false = true

  [or1 ]  true  or bool  = true
  [or2 ]  false or bool  = bool
  [or3 ]  bool  or true  = true
  [or4 ]  bool  or false = bool

  [and1]  true  and bool  = bool
  [and2]  false and bool  = false
  [and3]  bool  and true  = bool
  [and4]  bool  and false = false
end Booleans
```

This module defines and exports the sortname BOOL, lexical syntax for BOOL-constants, and context-free syntax for the prefix unary "not" and infix binary "and" and "or" operators, and for bracketing subexpressions. The separation between the lexical syntax part and the context-free syntax part gives the distinction of what is recognized by the scanner and what is recognized by the parser. Literals occurring in context-free syntax definitions are transferred to the scanner as well, so we could have defined the boolean constants in this section also.

With the syntax just made, we can enter terms like "true", "false", "true or false" etc. But what happens to a term like "true or false or true"; should this be treated as "(true or false) or true" or as "true or (false or true)"? This ambiguity problem is solved by the associativity attribute *left* attached to the functions "and" and "or", so the expression mentioned is parsed as "(true or false) or true". Other possible associativity attributes are *right*, *assoc* and *non-assoc*.

In the priorities section we stated that the relative priority of "not" to be higher than the priority of "and" and "or". Therefore an expression like "not true and false" is interpreted as "(not true) and false" (yielding false) and not as "not (true and false)" (yielding true).
Ambiguity problems which arise from intermixed use of "and" and "or" are solved by the group associativity attribute *left* in the priorities section, stating that "true and false or true" should be parsed as "(true and false) or true". Other possible attributes are: *right* and *non-assoc*.

The context-free function "(" BOOL ")" -> BOOL is meant to group boolean expressions in order to circumvent the associativities and priorities specified. The attribute *bracket* is attached to it, so this function will not appear in the derived abstract syntax for the boolean language.

We also declared an infinite set of boolean variables in the appropriate section of the exported language. The names of these variables can be used in the equations and follow the given syntax, so bool, bool1, bool789, bool', bool7" are all legal boolean variables.

The equations specify the behaviour of booleans in a derived term rewriting system. They follow the normal rules for truth tables. After having read our specification into the system, we can enter a term over the boolean language, for example "true or not true and false". This term is syntactically correct and can thus be parsed by clicking the mouse somewhere in the term, e.g. on the second "true". Then we get a focus on this subterm and we can inspect our language clause by moving this focus around. The following in an example showing the repeated zooming out of the focus (indicated by outlined character format):

true or not true and false
true or not true and false
true or not true and false
true or not true and false

Focus movements are based on the traversal movements in a syntax tree: zoom in (down to first subnode), zoom out (one node up), next child (to the right on same level), previous child (to the left on same level).

The modification of modules (syntax or equations) and the editing of a term, including focus movement, is done by using a generated text and structure editor GSE, see [3]. Such an editor is generated from a syntax definition: the syntax for booleans generates GSE instances specially tailored to the boolean language. Editing SDF modules follows the same principle: an editor is generated based on the syntax definition of an SDF module (either syntax- or equation modules).

Beside normal edit functions and focus positioning, these editors allow us to build and/or inspect terms in the specified language by means of the 'expand' menu. Open terms in our language may contain so called meta-variables (sortnames surrounded by "<" and ">") which can be replaced with one of the options from the expand menu. We will build the term from above using this feature:

<BOOL>	(expand: BOOL and BOOL -> BOOL)
<BOOL> and <BOOL>	(mouseclick)
<BOOL> and <BOOL>	(expand: BOOL or BOOL -> BOOL)
<BOOL> or <BOOL> and <BOOL>	(mouseclick)
<BOOL> or <BOOL> and <BOOL>	(expand: BOOL; typing "true")
true or <BOOL> and <BOOL>	(mouseclick)
true or <BOOL> and <BOOL>	(expand: not BOOL -> BOOL)
true or not <BOOL> and <BOOL>	(mouseclick)
true or not <BOOL> and <BOOL>	(expand: BOOL; typing "true")
true or not true and <BOOL>	(mouseclick)
true or not true and <BOOL>	(expand: BOOL; typing "false")
true or not true and false	

In conjunction with a closed term, the expand menu can be used to determine the sort of a subterm; this feature is especially handy when we edit lists or when we have terms over subsorts (by injection of one sort into another).

Now we have a well formed term in the boolean language, we can reduce this term to its normal form in the corresponding TRS by rewriting it repeatedly using the equations given. Our term will be reduced as follows:

true or not true and false	(rule [not1])
true or false and false	(rule [or1] or [or4])
true and false	(rule [and11] or [and4])
false	(rule [not1])

To give a more elaborate example of a specification in ASF+SDF, we will add another module which specifies a datatype *sets*. A set is defined as a collection of zero or more elements between curly braces, separated by comma's, such as in: {Monday, Tuesday, Wednesday, Thursday, Friday}. Elements of a set are defined as either a capital letter followed by letters or digits, or one or more digits. Defined operations on sets are union ("+"), difference ("-") and intersection ("*"). We also defined a grouping function and a set-membership predicate "in".

```
module Sets
imports
  Layout
  Booleans
exports
  sorts
    ELEM SET
  lexical syntax
    [A-Z][A-Za-z0-9]*    -> ELEM
    [0-9]+               -> ELEM
  context-free syntax
    "{" {ELEM ","}* "}"  -> SET
    SET "+" SET          -> SET  { right }
    SET "-" SET          -> SET  { right }
    SET "*" SET          -> SET  { right }
    "(" SET ")"          -> SET  { bracket }
    ELEM "in" SET        -> BOOL
  variables
    "elem" [0-9']*       -> ELEM
    "set" [0-9']*        -> SET
hiddens
  variables
    "e"[0-9']*           -> ELEM
    "e*"[0-9']*          -> {ELEM ","}*
    "e+"[0-9']*          -> {ELEM ","}+
equations
  [norm ] {e*1, e, e*2, e, e*3} = {e*1, e, e*2, e*3}
  [union] {e*1} + {e*2} = {e*1, e*2}
  [diff1] { } - {e*} = {}
  [diff2] {e, e*1} - {e*2} = {e} + ({e*1} - {e*2})
          when e in {e*2} != true
  [diff3] {e, e*1} - {e*2} = {e*1} - {e*2}
          when e in {e*2} = true
  [intr1] { } * {e*} = { }
  [intr2] {e, e*1} * {e*2} = {e} + ({e*1} * {e*2})
          when e in {e*2} = true
  [intr3] {e, e*1} * {e*2} = {e*1} * {e*2}
          when e in {e*2} != true
  [elem1] e1 in { } = false
  [elem2] e1 in {e2, e*2} = true
          when e1 = e2
  [elem3] e1 in {e2, e*2} = e1 in {e*2}
          when e1 != e2
end Sets
```

A feature not yet discussed in the SDF formalism, is the definition and treatment of lists. In general a list structure is defined as: {<sortname> <separator>}⊗ where <separator> is a terminal and ⊗ is either "*" or "+". This denotes zero or more resp. one or more repetitions of subterms of the proper sort, separated by <separator>. Without <separator> we also may write <sortname>⊗. Also variables may be of such a list sort, see for example the declaration of variables "e*" and "e+". We declared these in the hiddens section of module Sets, so they will not appear in the exported syntax.

Another feature, conditional equations, can be found in several equations of module Sets. The general syntax of an conditional equation is either

[...] t1 = t1', t2 = t2', ..., tn = tn' ==> t = t'

or

[...] t = t' when t1 = t1', t2 = t2', ..., tn = tn'.

both stating that we rewrite t to t' after we proved to be able to rewrite ti to ti' for i = 1..n.

The first equation of module Sets, [norm], will remove duplicate occurrences of an element in a set. A union of two sets is easily defined as a listing of all elements of both sets, provided that the former rule removes duplicates. As an example we get the following reduction:

{red, yellow, blue} + {red, white, blue} ->
{red, yellow, blue, red, white, blue} ->
{red, yellow, blue, white, blue} ->
{red, yellow, blue, white}

Testing for duplicate elements each time a set is manipulated in the rewriting process, is quite inefficient. Therefore we comment out the normalization rule and introduce an explicit unique operator:

```
"unique" SET          -> SET
%% [norm ] {e*1, e, e*2, e, e*3} = {e*1, e, e*2, e*3}
[uniq1] unique { } = { }
[uniq2] unique {e,e*} = {e} + unique ({e*} - {e})
```

The operators "-" and "*" are defined in terms of the set-membership predicate "in". The definition of this boolean function has a nasty property: it is based on (in)equality of terms, more precise it is based on (in)equality of normal forms of terms of sort ELEM. If we want elements like 1, 736, 004, etc. to be treated as numbers, we will not get the right membership function. Since leading zero's will not be removed, 004 does not equal 4 and so "4 in {004}" will yield false. One solution is to make sure that all ELEM's have one unique normal form:

```
variables "Chars" -> CHAR+
[norm] elem("0" Chars) = elem(Chars)
```

We defined a variable "Chars" to be one or more occurrences of the predefined sort CHAR. Next, we added an equation which makes sure that leading zero's of a term of sort ELEM are automatically removed. The function elem(CHAR+) -> ELEM is provided by the system for all lexical sorts. These functions allow us to manipulate lexical objects at a low level. A sample reduction will be:

```
004 in {1, 2, 3, 4, 5, 6, 7, 8} ->
04 in {1, 2, 3, 4, 5, 6, 7, 8} ->
4 in {1, 2, 3, 4, 5, 6, 7, 8} ->
4 in {2, 3, 4, 5, 6, 7, 8} ->
4 in {3, 4, 5, 6, 7, 8} ->
4 in {4, 5, 6, 7, 8} ->
true
```

In practise, we will have some basic datatypes T at our disposal, with at least the equality function defined on them (T "=" T -> BOOL), and then define a constant set as "{" {T ","}* "}" -> T_SET.

An even better suggestion, not supported by the current ASF+SDF implementation, is the possibility to parameterize module Sets with sort ELEM and the equality function. Binding the parameters ELEM and "=" with an actual sortname of a datatype and an equality function, results in a proper set definition of that datatype.

We have not added a priorities section to our specification of sets, but we could have done this as follows, giving the priorities we suggested in section 2.1:

```
priorities
  "#" > "*" > {right: "+", "-"}
```

which states that A # B * C + D - E is treated as if we had written ((A # B) * C) + (D - E).

3 A specification of a relational database system.

In this chapter we shall describe a specification for a relational database system, called RDBS. We have given a full listing of the work actually done in the appendices, here we describe how the work was done and why it has been done that way.

Serving as an illustration for the kind of system we want, resembling much the examples given in the introduction, we present a sample database and some operations on them in §3.1. We will revert to this example in many cases in the rest of this document.
Then, we describe the modular structure in §3.2 and more about the details of expressions and relations in §3.3 and §3.4 respectively.
Finally, in §3.5 we show the result of evaluating our sample database in §3.6.

3.1 Sample database

The following serves as our sample database; it consists of a schema, database and a program:

```
schema
   Sports        == {<'Zwemmen'>, <'Tennis'>, <'Wandelen'>, <'Voetbal'>}
   Numbers       <= {<n> @ Integers | (n >= 800000) & (n <= 919999)}
   Amounts       <= {<x> @ Reals | (amount >= 0.0) & (amount <= 300.0)}
   Students      <= {<number, name, phone> @ Numbers # Strings # Strings}
   Members       <= {<number, sport> @ Numbers # Sports}
   Contributions <= {<sport, amount> @ Sports # Amounts}
   Account       <= {<name, phone, amount> @ Strings # Strings # Amounts}
   Swimmers      <= {<name> <- <number, name, phone> @ Students}
database
   Sports = {<'Zwemmen'>, <'Tennis'>, <'Wandelen'>, <'Voetbal'>}
   Students = {
      <891247, 'Al-Hassan', '02990 - 42185'>
      <893218, 'Bakker', '020 - 6123316'>,
      <896673, 'Jansen', '020 - 6123316'>,
      <901274, 'The', ''>}
   Members = {
      <891247, 'Tennis'>,
      <893218, 'Zwemmen'>,
      <893218, 'Tennis'>}
   Contributions = {
      <'Zwemmen', 50.00 >,
      <'Tennis', 75.00 >,
      <'Wandelen', 1.50 >}
   Swimmers = {<name> <- <n1,name,p,n2,sport> @ Students # Members |
                  (n1 = n2) & (sport = 'Zwemmen')}
   Account = { }
   X = { }
   Y = { }
program
   Students <- Students + {<910001, 'Nieuwland', '015 - 147203'>};
   Students <- Students - {<number,name,phone> @ Students | number = 901274};
   Contributions <- {<sport,amount * 1.10> <- <sport,amount> @ Contributions};
   Account <- {<number, name, amount> <-
                  <number, name, phone, number2, sport1, sport2, amount> @
                  Students # Members # Contributions |
                  (number = number2) & (sport1 = sport2)};
   X <- Swimmers;
   Members <- Members + {<910001, 'Zwemmen'>};
   Y <- Swimmers;
end
```

The schema-part of this example is used to define the relations, their attribute names, and corresponding domains. The domains Booleans, Integers, Reals and Strings are some predefined datatypes. Sports, Numbers and Amounts are typical examples of user-defined domains. Students, Members, and Contributions are the relations in which we really put data in the database (base relations). Account and Swimmers are relations intended to gather derived information from the base relations. Swimmers is an example of a view which keeps track of student names who are enlisted for the swimming course.

The database-part lists the actual contents of the relations, i.e. the base relations and the temporary relations X and Y. Here we see the actual definition of the view Swimmers: a query on the product of Students and Members.

The program following the schema and database contains a list of zero or more statements which are assignments of the form: RelationName "<-" RelationalExpression ";".
The first of these statements is a special case of union namely the addition of a new student to the Students relation. The next one makes use of the assumption that each student has a unique student number, so this statement removes a student from Students. The increase of contribution with 10% is an example of a database update by using the extended projection. A conditional update, e.g. an increase of only some contributions, although it looks a little bit laborious, can be expressed as well.

The program continues with a query of what amounts have to be paid and by whom, after the update of the Contributions. The last three statements show the use of a view: after a student is enrolled or deregistered from some sport by insertion or deletion of a relevant entry in the Members relation, the use of Swimmers is automatically updated with this change.

3.2 Modular structure

Our specification of a relational database system has been divided over several modules. The import graph representing the import of modules in one another is given in Figure 1 in which M1 --> M2 means: M1 is imported in M2 or, equivalently, M2 imports M1:

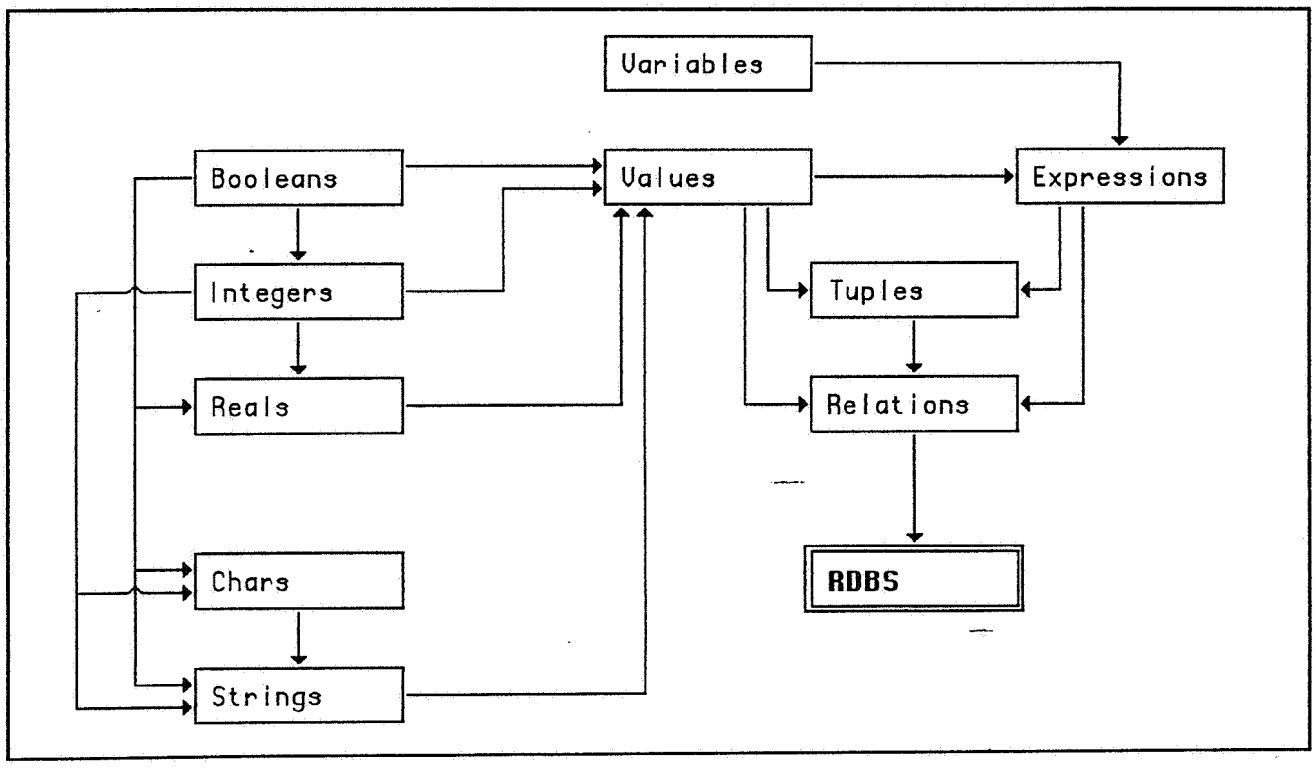

Figure 1: Import graph of RDBS modules.

The import relations shown are the explicit imports as can be found in the imports section of the modules. Implicit imports, like Chars in Values via Strings, are not shown since we actually did not want the signature of Chars appearing in Values (SDF has not yet a mechanism for restricting exported syntax). We could have left out the import of Booleans in Values, because this is implicitly done via the import of e.g. Reals in Values; but leaving out Reals from Values may not result in loosing Boolean syntax in Values!

Not shown in Figure 1 is the general occurring import of modules Layout and Lisp.

Layout defines the necessary layout characters space, tab and newline and the notion of comment (either two percent signs initiate comment till end of the line or all text between two percent signs is considered as comment). This module also exports some CHAR variables, which are needed for several low-level functions which are automatically provided by the system for all lexical definitions.

Lisp defines relevant syntax for hybrid implementations [9], like we have done with Reals and Chars [see §3.3].

The general ideas behind this modular structure are as follows:

1. the availability of a library of (predefined) datatypes like Booleans, Integers, Reals, and Strings with the possibility to extend these with newly needed datatypes,
2. the combination of values (belonging to some datatype) with variables to form expressions,
3. the binding of variables in an expression, i.e. replacing such a variable with an actual value, and calculation of the result,
4. a specification for a datatype *tuple* (i.e. a row of objects), preferable parameterized with the objects to be placed in these tuples,
5. definition of relations and implementation of all (set- or relational-) operators, and
6. definition and actual implementation of database assignments in a schema-datbase-program.

These issues return also in the next two paragraphs.

3.3 Expressions

In this section we describe the underlying datatypes, expressions over these datatypes and calculation of the results by binding values to variables. We will present the relevant modules bottom-up: 'higher' modules import and use the syntax defined in 'lower' modules.

First, we define the needed datatypes for our database system (booleans, integers, reals and strings), preferably each in its own module. The definitions include sortnames, constants (generally in the lexical section), operations (with their associativity and priorities properties), some predicates (at least equality and inequality, and other comparisons when an ordering can be defined) and variables of the newly defined sorts. These separate modules, possibly from a predefined library, together with a definition of variables can then be combined to form the kind of expressions we want.

Note incidentally the dual meaning of the symbol "=" in e.g. module Booleans. We would like to express the fact that two booleans are considered equal when they have the same normal form:

$b1 =_1 b2 \Longrightarrow b1 =_2 b2 =_1$ true.

Only because we can surround b1 = b2 with the bracket-function (BOOL) -> BOOL, the ambiguity of $b1 =_2 b2 =_1$ true can be resolved without user-interaction.

Module Integers specifies the arithmetic operations additions, subtraction and multiplication and the greater-than predicate using a lookup function LIST "." DIGIT -> INT, which speeds up the calculations considerably (O(logn) instead of O(n)). For implementation of datatype real in module Reals, we decided to use the hybrid feature of ASF+SDF. Main consequence thereof is that REAL's follow the lexical syntax of reals in Lisp. Note that in both Integers and Reals extra equations are needed for dealing with the negative cases (- INT and - REAL).

Module Chars is just there to provide some comparison predicates on single characters as a basis to define comparison on strings. Since the alternative is to write out at least 256 equations like ord('A') = 65, we again made use of hybrid implementation, namely for a hidden function ord(CHR) -> INT (note that sortname CHAR is unfortunately already taken). By the way, a CHR is lexically defined as some character, followed by a tilde "~" and not as a character between single quotes to avoid the ambiguity with a string-constant of just one character.

Module Strings implements strings (also an auxiliary function length(STR) -> INT and the operation INT "*" STR -> STR, i.e. 80 * '=' will give a nice page separator).

Having 'all' the datatypes we need, we can combine them into a single sort VAL (stands for 'value') by means of injection. This is done in module Values, which also defines some auxiliary functions involving intermixed sorts. The special value "null" is used to denote the unknown or unavailable value as mentioned in the introduction.

Arrived here we can write down expressions like true and false = true, 'hello' + 'there' or 16 + 48 but not expressions like 'hello' + 48" or false = 0.

In order to be able to perform queries on our database, we need variables which can hold a value of some datatype. So first we define the syntax for variables: as usual these variables follow the syntactic rules of an identifier, as can be seen in module Variables.

The easiest way to incorporate variables into expressions is to inject the sort VAR into the subsequent datatype sorts (e.g. VAR -> STRING or VAR -> VAL). Then we can unambiguously write down 100 + a but not 100 + '4'. Expressions like a + b however result in 2n + 1 ambiguities when n is the number of distinct datatypes. Later on, after binding values to variables, the expressions are evaluated correctly, that is 100 + 4 reduces to 104 and 100 + '4' will not occur.

After using the interactive disambiguator extensively, we decided to adopt another method. Another reason for this is that we could not write down an expression like 100.0 + 4 since the function REAL "+" INT -> REAL does not exist. Although we can provide such a function, or force the user to use typecast functions, the following method is more elegant.

Module Expressions defines the sort EXPR, which includes variables, the basic datatypes and all the operators we want for expressions. Valid expressions are a = b, 4 + 'zip' and true & false. Note that now the last of these expressions is ambiguous: either BOOL & BOOL -> BOOL or EXPR & EXPR -> EXPR. At least the following methods to solve this ambiguity exist:

1. rename all the overloaded functions on 'lower' datatypes, like renaming +: INT # INT- > INT into plus(INT,INT) -> INT, but this would contradict our idea to define datatypes separately in a library,
2. the same renamings using a renaming mechanism in the specification (does not exist in ASF + SDF),
3. use the priorities to force the system to choose among the possibilities, e.g. "INT + INT -> INT" > "EXPR + EXPR -> EXPR" or v.v. (not possible in ASF + SDF this way), or
4. hiding of the automatic export of the 'lower' functions to the outside world (also not implemented in ASF+SDF; all imported syntax is also exported automatically).

Since expressions only involving constants, like true & false or 4 + 17 > 12 will occur only in rare situations (false resp. 21 > 12 or simply true will suffice), we have let these ambiguities for what they are.

Evaluating an expression is done by binding variables in the expressions, i.e. replacing each occurrence of a variable with an actual instance (value) of that variable. Since we hold values, variables and expressions in lists (tuples, rows), we refer below to module Tuples for this binding mechanism. The result of a binding is an expression without variables, so only involving constants of one or several datatypes.

Example 1
Suppose we have two variables a and b with values 4 and 6 respectively. Replacing the values for the variables in the expression a + b >= 10 results in 4 + 6 >= 10 and is then evaluated as 10 >= 10, yielding true.
X

Evaluation of these 'closed' expressions is done by the equations of module Expressions. The following notes apply to these equations:

- Functions like sort(SORT) -> SORT, e.g. bool(BOOL) -> BOOL, had to be provided for forcing the type of the argument; see for instance the equation
  [add1] _Expr1 + _Expr2 = int(_Int1 + _Int2) when _Expr1 = _Int1, _Expr2 = _Int2.
  Via this typecasting the function "+" is 'forced' to be integer addition instead of expression addition.

- For each expressions function all combinations of all datatypes had to be considered meaningful; although REAL "+" INT -> REAL (and v.v.) was not provided by the datatypes we can simulate this function as has been done in the equation
  [add3] _Expr1 + _Expr2 = real(_Real + itor(_Int) when _Expr1 = _Real, _Expr2 = _Int.

- Combinations of datatypes in functions which are not meaningful are evaluated to "null". Since there is no default mechanism in the ASF + SDF formalism, we had to write out nearly all erroneous combinations, see for example the equation [add6] - [add25] (we have not completed this for many other combinations).

- The treatment of *null* in predicates is worked out completely (conform the tri-state truth tables of SQL; see §5.18 <search condition> General Rules 2 with *null* serving as the notion ***unknown***).

Module Tuples defines the several types of tuples we need; a module parameterized with the objects to put in the tuples would be preferable. Beside tuples, this module also implements the promised function bind(INST_TUP,EXPR)->EXPR, the first argument being a tuple of variable instances (pairs VAR ":" VAL) and the second an expression to evaluate. As an example we show the following reduction:

Example 2
bind(<i : 4, b : true, s : 'actual'>, (i * i > 16) & b & s = 7) -> ... ->
(4 * 4 > 16) & true & 'actual' = 7 -> ... ->
false & true & null -> ... -> false
X

Writing down the equations for this binding is, again, just working down all the cases which form an expression. Two other useful functions are implemented:
- inst(VAR_TUP,VAL_TUP)->INST_TUP (instantiate variables with values) and
- val(EXPR_TUP) -> VAL_TUP (conversion of tuples with expressions to tuples with single values by implicit evaluation of the expressions).

The following serves as an illustration of these last two functions.

Example 3
Suppose we want to extract information from a relation Employee with name and salary as attributes. At some point in this process we reach the employee <'Jones', 100>. The information to be derived is the employee's name and salary after an increase of 10%. The following reduction will then occur:
val(bind(inst(<name, salary>, <'Jones', 100>), <name, salary * 1.10>)) ->
val(bind(<name: 'Jones', salary: 100>, <name, salary * 1.10>)) ->
val(<'Jones', 100 * 1.10>) ->
<'Jones', 110>
X

Before discussing our specification for relations and more, we would like to sketch how to add a newly defined datatype, e.g. DATE, to the system:

1. specify the datatype of sort DATE in one or more modules with top-module Dates,
2. import Dates into Values and add "DATE -> VAL" in the context-free syntax section,
3. import Dates into Expressions and, for each operator or function, write out all the combinations with at least one argument of sort DATE and determine the corresponding result,
4. add the equation "[..] bind(<_Var : _Date, _Insts>, _Var) = _Date" when _Date is a variable of sort DATE , and
5. when a function of sort DATE has to be lifted to a function of sort EXPR, which e.g. could be the case with day-of-week(DATE) -> STR, this function has to be declared and specified in Expressions and the implementation of the function bind() must be expanded too.

3.4 Relations, Databases

Relations, with sortname REL for short, are defined in module Relations. Constants of this sort follow the notation given in §2.1. The traditional set operations are all implemented, except for "/". The unique function "! " REL -> REL is provided to remove duplicate tuples from a relation.

The function VAL_TUP "@" REL -> BOOL should be read as the traditional 'element of' ($a \in S$) and EXPR_TUP "@" REL -> EXPR is added to the sort EXPR for allowing subqueries to be made (see below). The function "#" REL -> INT gives us the cardinality of a relation.

Two quantified predicates are provided by the functions
for_all VAR_TUP "@" REL : EXPR -> BOOL and
there_is VAR_TUP "@" REL : EXPR -> BOOL,
denoting the traditional predicates "$\forall x \in V$: p(x)" resp. "$\exists x \in V$: p(x)".

Example 4
for_all <x> @ {<3>, <4>, <5>} : x > 2 -> ... -> true
X

The largest element (tuple) of a relation can be extracted using sup(REL) -> EXPR, the smallest using inf(REL) -> EXPR and the summation of all values of a single column, provided they are all integers ór reals ór strings (as should always be the case since domains may not be mixed), is done by sum(REL) -> EXPR.

A selection from a relation can be made using {VAR_TUP @ REL | EXPR} which could best be read as a variant of the more common set definition, for example $\{<x,y> \in \Re \times \Re \mid x^2 + y^2 = r^2\}$. This defines a set of coordinates in the two-dimensional plane: a circle with radius r and middlepoint < 0, 0 >. In our case however the set to draw values from is always finite.
The selection {<n> @ {<1>, <2>, <3>} | n <> 2} results in a relation {<1>, <3>}.

The generalized projection function from the introduction can be made with the function
{ EXPR_TUP <- VAR_TUP @ REL }
and is best illustrated by giving an example.

Example 5
{<name, salary, salary * 1.10> <- <name, address, salary, start_date>_@ Employee}
This query will result, provided that a constant relation as intended is inserted in place of Employee, in a listing of the name, old salary and new salary (after a raise of 10%) of all employees.
X

Combining both functions gives us the function
{ EXPR_TUP <- VAR_TUP @ REL | EXPR }.

Example 6

```
{  <name, salary, salary * 1.10> <-
   <name, address, salary, start_date> @
   Employee |
   start_date < 1:1:91}
```

This will result in the same listing as before, but only of employees who were hired before Jan 1, 1991.

X

The function { VAR_TUP @ REL } is defined for those who like to simulate the SQL query "SELECT * FROM R".

The first equation of module Relations, which is commented out for our purpose, can be used as a normalisator: duplicate tuples are found and removed from a constant relation. We saw this before in §3.3 and closer inspection tells us again that the equality of tuples is based on the equality of all corresponding values. This is not valid however when some datatype does not provide one and only one normal form for two different representants of the same equivalence class. This turns out to be the case for Reals: "004.600" is not textually equal to "4.6". Therefore we defined the equality of tuples in module Tuples and we used it in the implementation of VAL_TUP @ REL -> BOOL.

The implementation of the relational operators is quite straightforward:
1. each time a tuple with values from the relation is taken,
2. the attributes are instantiated with these values,
3. the selection expression (when provided) is evaluated to see whether or not the tuple is selected, and finally, when the tuple is selected,
4. the expressions in the projection tuple (when provided) are evaluated to form the output value tuple.

Example 7 (compare also with the sample database)

```
{  <sport, amount * 1.10> <- <sport, amount> @
   {<'Zwemmen', 50.00>, <'Tennis', 75.00>, <'Wandelen', 1.50>} | sport <> 'Tennis'} ->
{val(bind(<sport: 'Zwemmen', amount: 50.00>, <sport, amount * 1.10>))} + *)
{val(bind(<sport: 'Wandelen', amount: 1.50>, <sport, amount * 1.10>))} ->
{val(<'Zwemmen', 50.00 * 1.10>)} + {val(<'Wandelen', 1.50 * 1.10>)} ->
{<'Zwemmen', 55.00>} + {<'Wandelen', 1.65>} ->
{<'Zwemmen', 55.00>, <'Wandelen', 1.65>}
```

*) Since
bind(<sport: 'Tennis', amount: 75.00>, sport <> 'Tennis') -> 'Tennis' <> 'Tennis' -> false,
the tuple <'Tennis', 75.00> will not be selected.

X

When evaluating a subquery: {<x> @ X | <x> @ {<y> @ Y | x = y}}, resulting in those values of X which occur in Y as well, we need to bind the variables in the inner expression x = y with values from the outside. If for example x has value 4 from the relation X, the bound predicate should look like "<4> @ {<y> @ {...} | 4 = y}". Therefore we extended the equations for bind(INST_TUP, EXPR) -> EXPR with the case that the argument is such a predicate and introduced another bind function rbind(INST_TUP, REL) -> REL, which substitutes variables for values inside a relational expression.
If we had chosen the same variable names in the example above, as in {<x> @ X | <x> @ {<x> @ Y | x >= 0}}, we surely don't want to substitute a value for the first x into the expression x >= 0. Function scope-cover(INST_TUP, VAR_TUP) -> INST_TUP removes instantiated variables from the instantiate tuple when they occur in the variable tuple given.

Finally, we reach module RDBS (acronym for Relational DataBase System), which defines the syntax and semantic needed to write down and evaluate a schema followed by an actual database and a program (alltogether an 'EXE'). Note from the equations that we do not need to encapsulate an EXE in an evaluation function. Whenever there is at least one statement in the program, it is evaluated automatically after pressing the reduce button.

The only possible statements in a RDBS program are assignments to a relation in the database, so the only form of output to the end-user is an updated database after execution of the program. Note that there is absolutely no checking whatsoever: the schema is not used for the execution of a statement, an assignment to a non-existing relation is cannot be done, use of an unknown relation is not prohibited, etc.

The main functions of this module are erel(SCHEMA, DBASE, REL) -> REL used to instantiate relation variables with constant relations from the database and eval(SCHEMA, DBASE, EXPR) -> EXPR to do the same, but with relations occurring inside a (value) expression.

Two types of queries are added to the syntax:
{EXPR_TUP <- @ REL | EXPR} and
{ @ REL | EXPR}.
They look like queries without a variable tuple indicating the attributes of the relation and so they are indeed. This type of query can be used to translate SQL queries; the corresponding attributes are looked up from the schema by using function attr(SCHEMA, REL) -> VAR_TUP. (Note: this is the only case where a schema is actually used.)

3.5 Return to the example

Here we return to the sample of §3.1. The result of the program applied to the database is a changed database and an empty program, as shown below:

```
schema
   Sports        == {<'Zwemmen'>, <'Tennis'>, <'Wandelen'>, <'Voetbal'>}
   Numbers       <= {<n> @ Integers | (n >= 800000) & (n <= 919999)}
   Amounts       <= {<x> @ Reals | (amount >= 0.0) & (amount <= 300.0)}
   Students      <= {<number, name, phone> @ Numbers # Strings # Strings}
   Members       <= {<number, sport> @ Numbers # Sports}
   Contributions <= {<sport, amount> @ Sports # Amounts}
   Account       <= {<name, phone, amount> @ Strings # Strings # Amounts}
   Swimmers      <= {<name> <- <number, name, phone> @ Students}
database
   Students = {
      <891247, 'Al-Hassan', '02990 - 42185'>
      <893218, 'Bakker', '020 - 6123316'>,
      <896673, 'Jansen', '020 - 6123316'>,
      <910001, 'Nieuwland', '015 - 147203'>}
   Members = {
      <891247, 'Tennis'>,
      <893218, 'Zwemmen'>,
      <893218, 'Tennis'>,
      <910001, 'Zwemmen'>}
   Contributions = {
      <'Zwemmen', 55.00 >,
      <'Tennis', 82.50 >,
      <'Wandelen', 1.65 >}
   Swimmers = {<name> <- <n1,name,p,n2,sport> @ Students # Members |
                  (n1 = n2) & (sport = 'Zwemmen')
   Account = {
      <891247, 'Al-Hassan', 82.50>
      <893218, 'Bakker', 55.00>,
```

```
    <893218, 'Bakker', 82.50>}
  X = {<'Bakker'>}
  Y = {<'Bakker'>, <'Nieuwland'>}
program
end
```

In this output database we see the changes to Students, Members and Contributions:
- addition of student 'Nieuwland' to Students,
- deletion of student 'The' from Students,
- enrollment of student 910001 ('Nieuwland') with sport 'Zwemmen' to Members, and
- increase of contributions (amount in relation Contributions) with 10%.

The relation Account is the list of payments to be done after the increase of contributions. (Note that in SQL it would have been possible to sum the amounts to be paid by student Bakker by using a grouping on student name or -number; this is not possible using relational algebra only.)

Finally, we see the effect of using a view by inspecting the contents of relations X and Y (Swimmers before and after enrollment of student 'Nieuwland' for 'Zwemmen'). In this case the administration would have been very pleased if the database designer had defined Account as a view also.

With just a view additions to this database system, like dynamic creation and destruction of relations, it has all the power to implement a ready-to-use relational database system in practice.

4 Syntax of SQL

In this chapter we describe the SQL syntax based on the standard definition.
First, the syntax from the BNF definitions is translated to a corresponding SDF syntax definition. Next, some preliminaries about typechecking SQL are given. Finally, typecheck functions for SQL schema's and query specifications are explained.

4.1 Conversion of BNF to SDF

The first step in specifying SQL is to translate the BNF definition given in the standard into lexical and context-free syntax of SDF. A main choice has to be made: whether to stay close to the BNF definition or to rearrange this syntax completely. Because the typecheck rules given by the Syntax Rules sections are very much related to the BNF definition, we have chosen for the first option.

The following steps describe how we converted the BNF definition, listed in Appendix A, into SDF.

1. A separation had to be made which language constructs to put in the lexical syntax part and which in the context-free syntax part. The main point of distinction here is whether or not layout is allowed between (non) terminals of the definition. Combining the BNF definitions and Syntax Rules of the standard, we decided to place §5.1 - §5.3 (<character>, <literal> & <token>) in the lexical syntax part.

2. All non-terminals of the BNF definition have been rewritten to form practical SDF sortnames: supply words with leading capitals, put words together (i.e. removing non-letters), and finally remove the surrounding brackets (so <table name> is converted to TableName). When these sortnames became too long, we abbreviated them, preferably in the common way (e.g. Identifier was shortened to Ident).

3. All terminals had to be surrounded by double quotes (e.g. <mantissa>E<exponent> is translated to Mantissa "E" Exponent).

4. Since ASF+SDF does not allow context-free functions to contain alternatives, optionals and grouping we had to rewrite these constructs, and repetitions as well, in the following way:

NonTerm ::= T_1 | T_2 | ... | T_n	->	NonTerm ::= T_1 NonTerm ::= T_2 ... NonTerm ::= T_n
[T...]	->	T*
T...	->	T+
NonTerm ::= e_1 [e_2] e_3	->	NonTerm ::= e_1 e_2 e_3 NonTerm ::= e_1 e_3

5. Grouping in extended BNF definitions, surrounded by braces { }, has in general to be replaced by a subsort. But in this situation it was not necessary to do so, because of the following reasons:
   - the syntax occurring in groups could be specified using lexical syntax only,
   - it were lists of simple alternatives (and were written out as above), and
   - the combination <non terminal> [{, <non terminal>}...] was replaced by the SDF comma-list construction {NonTerm ","}+.

6. Rules like NonTerm ::= E were reversed to E -> NonTerm

The sections of the definition we decided to become lexical syntax was treated different from the rest:
- the definitions for <character>, <digit>, <letter>, etc are incorporated in the other definitions (e.g. by replacing <digit> with [0-9]),
- a string literal does not follow the rules of the definition exactly because the <quote representation> within a <character string literal> met some difficulties (note that the empty string is not part of the SQL language, one should use NULL instead),
- <comment>, <space> and <newline> are translated to define the predefined sort LAYOUT, and

- the tokens and keywords of the language are derived from the SDF syntax automatically and in such a way that it follows the rules of the definition (the SDF 'prefer literals' rule for instance); therefore the sorts <token> and <keyword> are not specified in SDF.

7. In order to form a proper SDF module, we had to add a sorts section (by listing all distinct output sortnames of the syntax functions) and a variables section for later use (with names derived from the sortnames).

The final stage of translating the BNF definition of SQL is to split up the syntax so far into handy-to-use smaller modules. Figure 2 shows the import graph of these modules:

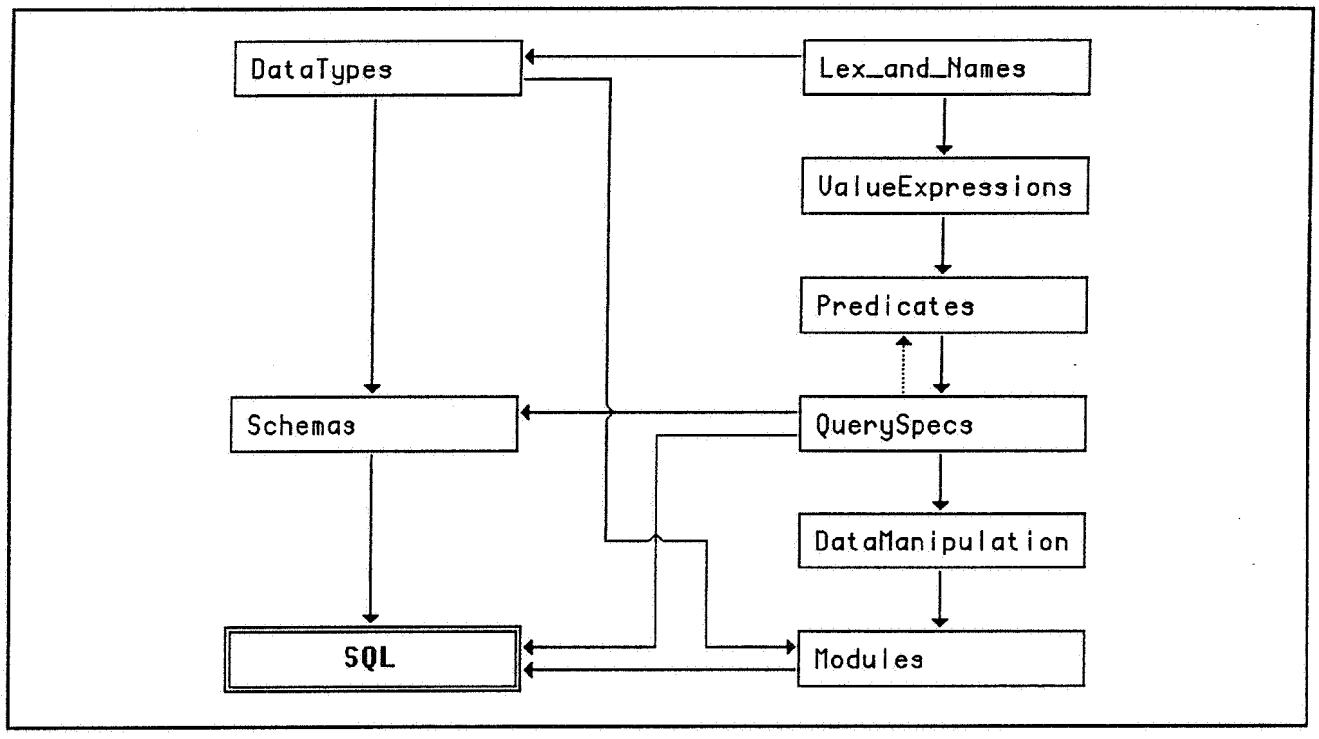

Figure 2: Importgraph SQL language.

Lex_and_Names: the lexical syntax from §5.1 - §5.3 and the 'names' from §5.4 (because these names occur practically everywhere).

ValueExpressions: all language constructs (§5.6 - §5.9) to define expressions resulting in a single value of some datatype (as opposed to TableExpressions and Predicates).

Predicates: the expressions resulting in a truth value true, false, or unknown (§5.10 - §5.17).

QuerySpecs: the main query function of SQL (§5.18 - §5.25).

DataTypes: the character string and various numeric datatypes of SQL (§5.5).

Schemas: the schema definition language to define schemas, tables, views, and privileges (§6.1 - §6.10).

DataManipulation: data manipulation language of SQL (statements) (§8.1 - §8.12).

Modules: module language of SQL (cursor and procedure declarations) (§7.1 - §7.3).

Note: DataTypes is the only module which contains equations; they implement automatically the Syntax Rules 1 and 3 of §5.5 <data type>.

The import of module QuerySpecs in module Predicates was also needed (dotted arrow in Fig. 2), since predicates can contain subqueries. A cyclic import is not allowed in ASF + SDF, so we left out this import. To avoid the error message 'sort SubQuery not defined' when dealing with predicates, we declared the sortname SubQuery in module Predicates and delayed the definition of this sort until module QuerySpecs. So, however it is possible actually, neither of these modules should be used without the other!

4.2 Typechecking preliminaries

Typechecking is the process of verifying fragments of a program source text with respect to information from an environment. In general we need a function: tc: ENV # PROG -> BOOL. The environment is usually a quickly accessible description of previously declared symbols (such as a symbol table containing declared identifiers with their type). During the process of typechecking we break down the language constructs into smaller pieces and check these smaller pieces accordingly. So we end up with a collection of functions, each capable of checking some construct in the language. We can either give them different names, like tc_prog, tc_stat etc, or use the overloading mechanism and call them all tc.

During this top-down typechecking process, we sometimes need to give extra information down to lower levels (so-called inherited attributes) and sometimes we gather information at lower levels (synthesized attributes) and pass this as a result back to the caller. Due to these synthesized attributes some typecheck functions need more than one output sort, like in tc: ENV # EXPR -> BOOL # TYPE.

A proper typecheck function shall not result in just "false" when the source text is found incorrect. Instead some sort of message about the kind of error detected and the location where the error took place is convenient for the user. (Beside pinpointing where the error took place, the ideal typecheck function tries to find out the reasons for an error and suggests possible solutions to fix the problem.) More than one of such a message must be given if more errors are detected in the source. We must however avoid winding up in generating errors due to errors previously found.

In the next paragraphs we shall describe a typecheck function for SQL. Not all of the language constructs of SQL have been done; only a significant subset. The constructs we have done are §5.1 - §5.25 (i.e. a <query specification> and all its components) and §6.1 - §6.6 (i.e. a complete <schema>) with exclusion of the following:
- column constraints, default clauses, table constraints, and privileges are not checked,
- parameters (SQL modules), and variables (embedded SQL statements) are excluded,
- argument and result of set functions (COUNT, SUM, etc.) are checked only for type,
- grouping of tables (select list group-by-, and having-clause) are checked only limited.

Facing the problem of typechecking SQL we have made the following choices:

1. Choosing the environment datatype:

As environment-parameter for a typecheck function for query specifications we use a more easily manageable and quicker accessible datatype than the language construct schema itself (or more accurate: the self chosen environment). An environment can be translated by the function envdescr(Environment, QuerySpec) -> EnvDescr from module SchemaDescr. Next, such a resulting environment description can be checked against the syntax rules from §6.1 - §6.6 by using the function envcheck(EnvDescr) -> ERROR. An OK-checked environment description can now be used for typechecking a series of queries typed by a user, as is done in module TypeCheck.

Using an environment description instead of an environment itself is easier manageable because of some reordering of entries (like privilege definitions separated from table- and view definitions) and because there is more uniformity (see for instance a description of a datatype: DTDescr). It is quicker accessible because there are less cases to be dealt with.

This choice however has one major drawback. When we want to convince someone that our typecheck function is conform the definition in the standard, we need to demonstrate that all syntax-rules are correctly checked based on a description and not on the source text itself. (Note that the standard defines descriptions of some language clauses.)

SDF allows us to incorporate language clauses such as Identifiers, Statements, or whatever, inside descriptions, simply by inserting them in the definition of the structure. We considered this new opportunity as a very practical feature.

2. Choosing the error message mechanism:

Instead of a fancy yet complex error message mechanism, which is beyond the scope of this thesis, we have chosen to present just simple and adequate error messages. Not just error messages in the form of strings, but we invented the type ERROR (see module Errors) in the following way:

- OK is the ERROR constant denoting that all is well.

- Mixing explanatory text with relevant language clauses is possible, as in:
  "Column" ColumnSpec "undefined!" -> ERROR
  in an equation:
  [..] check(_Env, _ColumnSpec) = Column _ColumnSpec undefined! when ...
  Additional information can be added to the message by providing more context:
  [..] check(_Env, _ValueExpr, _ColumnSpec) =
  Column _ColumnSpec undefined in _ValueExpr! when ...

- We used the binary operator ERROR "AND" ERROR -> ERROR to combine errors of mutual independent checks, as when checking lists of value expressions in a select list.

- The binary operator ERROR "AND" "THEN" ERROR -> ERROR is used to combine checks which are dependent in time, for example the query
  SELECT * FROM R WHERE R.A <> 0
  will result in an error message:
  Table Ref R undefined!
  instead of:
  Table Ref R undefined! AND Column R.A undefined!
  when R is not a table from the environment.

3. Choosing the moment to translate:

While typechecking language constructs, it is very tempting to look at the translation of these constructs as well. In many situations it is even a shame not to use the information determined during the typechecking. For instance when encountering an expression "IntVar + RealVar", the typecheck function knows that a conversion of the value of the integer variable IntVar to a real is needed. This information can be passed as a synthesized attribute for use by a translator. A translator based on the same unmodified language construct, has to determine again the type of both variables and the conversions needed.

We choose, however, not to think of translation during typechecking for the following reasons:

- Keep the size of the specification relatively small. Having the syntax and equations of both languages read into the system, and all typechecking and translation functions as well, it would soon be too large to execute.

- Since the target language of the translation of SQL is very flexible (the above case is dealt with automatically), we don't need so much 'type' information while translating.

- A clear separation between typechecking and translation is desirable when we want to anticipate on the possibility to translate SQL to other relational database languages than RDBS.

4. How to deal with views:

A view definition contains a query specification and can thus refer to other tables (or views) in its very definition, for example:

```
CREATE VIEW SWIMMERS (NAME) AS
    SELECT NAME FROM STUDENTS, MEMBERS
    WHERE  (STUDENTS.NUMBER = MEMBERS.NUMBER) AND
           (MEMBERS.SPORT = 'Zwemmen').
```

This leads to the following three consequences:

- We have to use all the syntax and semantics of checking query specifications for checking a schema too, which is not a problem when all functionality is available already, but has been somewhat difficult to design.

- When a column name in an expression is encountered during typechecking, one of the things to find out is to which table or view this column belongs and of what type it is. If the column belongs to a view, we have to dig out the type information from the query defining the view. For this reason we need to convert a view definition to something resembling an ordinary (base) table definition (see also §6.9 Syntax Rule 7 requiring such a description). Since a view definition can refer to other tables and views, we can only do this after checking the whole environment first.

- A view definition can refer directly or indirectly to itself, e.g. two views defined as queries upon each other; we did not try to solve this possibility (there are also no corresponding Syntax Rules in the standard).

The total typecheck function we implemented for SQL Schema's and QuerySpecs has been divided over several modules, as shown in Figure 3:

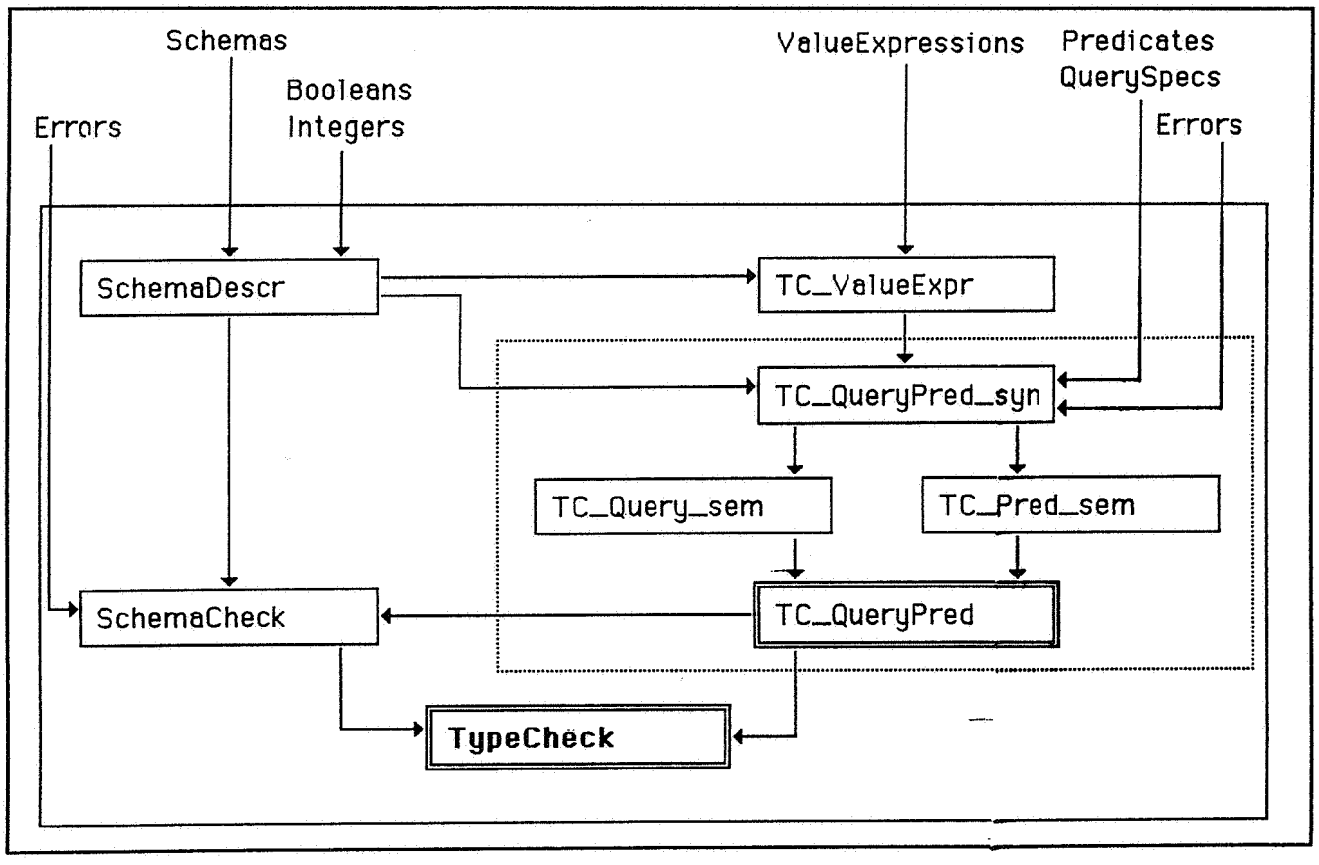

Figure 3: Importgraph of TypeCheck facility.

4.3 Typechecking SQL schema's

We will now describe the typechecking modules for SQL Schema's, SchemaDescr and Schema-Check.

SchemaDescr
- definition of the sort EnvDescr, the datatype for a description of an environment, and all its subtypes, and variables of sort EnvDescr,
- specification of the function env-descr(Environment) -> EnvDescr (and functions for describing lower language constructs in the hiddens section),
- two auxiliary functions lookup-table() and lookup-column().

An important datastructure is a so-called TVListDescr, which is a list of descriptions of table- or view definitions. This list is not only constructed when describing a schema and used for lookup of a table name, but also for determining the context of a value expression, i.e. what tables can be referred to using column names.
The result of function lookup-table(TableName, EnvDescr) -> TVListDescr is defined as all those tables whose name satisfies the TableName. For example table name R satisfies both S1.R and S2.R for schema identifiers S1 and S2; see also equations [eqtn1] - [eqtn4]. So given a table name, lookup() can find zero or more corresponding tables and thus we defined the output sort as a TVListDescr. The same idea holds for lookup-column(ColumnSpec, TVListDescr) -> ColListDescr, which finds zero or more columns given a column name and a list of tables.

Another heavily used structure is a DTDescr, the description of an SQL datatype. This is a tuple containing type (String, Exact, Approx or Notype), length or precision (Unsigned), and optional scale (Unsigned), e.g. <approx, 5, 2>. When no particular datatype can be determined, usually the 'constant' <Notype,0,0> is returned.
To determine a datatype we use the functions type(), length() and scale(). Type() determines the type description belonging to a datatype by simply matching with datatype's subsorts (equations [type1] - [type3]). Length() determines the length of a string type or the precision of a numeric type and scale() the optional scale of a numeric type.
The latter two functions do not need to specify all the cases a datatype can look like, because the equations of module DataTypes take care of abbreviations and defaults. So a possible reduction path is:

length(CHAR) -> length(CHARACTER) -> length(CHARACTER(1)) -> 1.

Example 1

```
env-descr( -
  CREATE ENVIRONMENT UNIVERSITY
    CREATE SCHEMA ADMINISTRATION
      CREATE TABLE SPORTS (
        SPORT   CHAR(10)
      )
      CREATE TABLE STUDENTS (
        NUMBER NUMERIC(6,0)
        NAME    CHAR(20)
        PHONE   CHAR(15)
      )
      CREATE TABLE MEMBERS (
        NUMBER NUMERIC(6,0)
        SPORT   CHAR(10)
      )
      CREATE TABLE CONTRIBUTIONS (
        SPORT   CHAR(10)
        AMOUNT NUMERIC(5,2)
      )
      CREATE VIEW SWIMMERS (NAME) AS
```

```
          SELECT NAME
          FROM STUDENTS, MEMBERS
          WHERE STUDENTS.NUMBER = MEMBERS.NUMBER
          AND SPORT = 'Zwemmen'
)
->
< UNIVERSITY,
  [ < ADMINISTRATION,
    [ < ADMINISTRATION, SPORTS,
        [ < SPORT, String, 10, 0>, NULL, false> ],
        []
      >
      < ADMINISTRATION, STUDENTS,
        [ < NUMBER, Exact, 6, 0>, NULL, false>,
          < NAME, String, 20, 0>, NULL, false>,
          < PHONE, String, 15, 0>, NULL, false> ],
        []
      >
      < ADMINISTRATION, MEMBERS,
        [ < NUMBER, Exact, 6, 0>, NULL, false>,
          < SPORT, String, 10, 0>, NULL, false> ],
          []
      >
      < ADMINISTRATION, CONTRIBUTIONS,
        [ < SPORT, String, 10, 0>, NULL, false>,
          < AMOUNT, Exact, 5, 2>, NULL, false> ],
        []
      >
      < ADMINISTRATION, SWIMMERS,
        [ NAME ],
        SELECT NAME
        FROM STUDENTS, MEMBERS
        WHERE STUDENTS.NUMBER = MEMBERS.NUMBER
        AND SPORT = 'Zwemmen',
        false
      >
    ],
    []
    >
  ]
>
X
```

SchemaCheck

- specification of the function tc(EnvDescr) -> ERROR, which checks a description of an environment and resulting in either OK or some applicable error message(s),
- specification of expand-env(EnvDescr, EnvDescr) -> EnvDescr, which converts a description of a view to a description of a (base) table after the typecheck has succeeded.

Note the arguments to expand-env(): the first EnvDescr is used as a lookup for expansion of the second one, resulting in the output EnvDescr. So when calling this function, it is preferred to use the same argument twice.

Example 2

```
tc(env-descr(
  CREATE SCHEMA S
    CREATE TABLE A.T (
```

```
      C CHAR(1)
      C NUMERIC(1)
    )
    CREATE TABLE S.T (
      C CHAR(1)
    )
))
```

Possible errors are:
- Authorization Id A should be S!
- Table Name T should be unique!
- Column Name C should be unique! (only in first table)

Only the first of these errors will be returned in our implementation.
X

Example 3
In a number of steps we show the typechecking of the view Swimmers from the sample database.

```
tc(env-descr(
  ...
    CREATE VIEW ADMINISTRATION.SWIMMERS (NAME) AS
      SELECT NAME
      FROM STUDENTS, MEMBERS
      WHERE STUDENTS.NUMBER = MEMBERS.NUMBER
      AND SPORT = 'Zwemmen'
  ...
)
```

The error messages
Authorization Id ADMINISTRATION should be ADMINISTRATION!
and
Table Name SWIMMERS should be unique!
will not occur, since the corresponding conditions of equations [tv2] and [tv3] fail.

At this point equation [tv3] will come into action: query-check(E, Q), where E is the environment description and Q the query specification from the view definition, will result in a list column descriptions (one in this case):
[<NAME, <String, 20, 0>, NULL, [], false>],
provided that Q is OK-checked (see below for query-check()).

This list column descriptions is matched against the view column list, "(NAME)", using function vcoll-check(). The check to be performed:
should-provide-viewcolumnlist() AND THEN
all-ids-must-be-different() AND THEN
right-number-of-viewcolumns()
will yield OK, since
- a view column list ís provided,
- NAME is the only identifier in this list, and
- the query specification Q results in a single column.

After expansion using expand-env() this view definition will have as description:
<ADMINISTRATION, SWIMMERS, [<NAME, <String, 20, 0>, NULL, [], false>], []>.
X

4.4 Typechecking SQL query specifications

In this section we explain the modules for typechecking SQL queries.

TC_ValueExpr
- definition of sort VE_EDP (ValueExpression_ErrorDescriptionPair) and
- function ve-check(TVListDescr, ValueExpr) -> VE_EDP.

The function ve-check() checks a given value expression against the rules from the definition and with respect to the context TVListDescr. The latter argument is mostly derived from a list of tables in a from clause as part of a query specification and mainly used for looking up a given column in this list. Note the use of lookup-column() to see wether a column specification refers to a unique column, an ambiguous column, or no column at all in the given context (equations [c1] - [c3]).
The result of ve-check() applied to an expression is either an error message not equal to OK and some undefined datatype, or an OK message and the description of a datatype.

Note: it turned out to be very difficult to determine the precision and scale of an exact numeric literal. The precision is defined as the number of digits and the scale as the number of digits right from the (implicit) decimal point (§5.2 <literal> Syntax Rule 4). Our implementation is only partial correct.

Example 4

SELECT STUDS.NUMBER FROM STUDENTS, MEMBERS

The select list STUDS.NUMBER of this query about our sample database, can result in the following typecheck error messages:
- Type of operand(s) of '+' may not be string!
- Column STUDS.NUMBER undefined!
- Column NUMBER ambiguous! (after removal of "STUDS.")

X

Example 5

Suppose someone is interested in the following query about our sample database:

SELECT AVG(AMOUNT) + 1.0 FROM CONTRIBUTIONS.

With the current values in our database, this query will result in the value 43.17.

First, we show how the exact literal 1.0 will be checked:

ve-check(1.0) -> [ve11]
<OK, <Exact, precision(1.0), scale(1.0)>> -> [prec3] & [scale1]
<OK, <Exact, 2, 1>>

Also, the column reference AMOUNT will be checked:

ve-check(AMOUNT) -> [ve13]
c-check(AMOUNT) -> [c1] (*)
<OK, <Exact, 5, 2>>

(*) Since lookup-column(AMOUNT, ...) results in exactly 1 column description, AMOUNT is defined and unambiguous.

Since the error part of the last result is OK and the type is not String, AVG(AMOUNT) will be checked using equation [ve26]:

ve-check(AVG(AMOUNT)) -> [ve26]
<OK, <Exact, 5, 2>>

The value expression AVG(AMOUNT) + 1.0 will be checked:

ve-check(AVG(AMOUNT) + 1.0) -> [ve1]
exp-check('+', ve-check(AVG(AMOUNT)), ve-check(1.0)) -> (see above)
exp-check('+', <OK, <Exact, 5, 2>>, <OK, <Exact, 2, 1>>) -> [exp4] (*)
<OK, <exp-type(Exact, Exact), exp-prec(5,2), exp-scale('+', 2, 1)> -> [etyp1],[epr1]&[esc1]
<OK, <Exact, 5, 2>>

(*) Since both errors are OK and none of them are of type String.

So the value expression given in the query is type correct (OK) with type exact numeric, precision 5 and scale 2; therefore the result is 43.17 and not 43.16666 for instance.
[X]

Just like the distribution of the SQL language over several modules, we would like to divide the typecheck function into modules TC_Predicate and TC_Query. For typechecking subqueries in predicates, we need the functionality to check queries and vice versa. In order to solve this cyclic use, we created the modular hierarchy outlined in Figure 3 (dotted lines). Module TC_QueryPred_syn defines all the common syntax for typechecking both queries and subqueries. Modules TC_Query_sem and TC_Pred_sem implement the semantics (equations) of this syntax (and local functionality as well). Module TC_QueryPred finally combines these modules in order to form one coherent signature to the outside world.

TC_QueryPred_syn
- definition of several output tuples to hold an error and synthesized attributes
- syntax of several check functions, one for each main language clause

TC_Pred_sem
The main function of this module is pred-check(EnvDescr, TVListDescr, Predicate) -> ERROR, which just handles all the cases a predicate can look like. The second argument, TVListDescr, stems from a preceding from clause: it determines the context which table- and column names can be used. The first argument, EnvDescr is not used, but handled over to a possible subquery in the predicate (see for instance an InPredicate: ValueExpr IN SubQuery).

Example 6
```
SELECT *
FROM MEMBERS
WHERE N NOT IN (SELECT NUMBER, NAME FROM STUDS)
```

This query about our sample database, finding non-students who are enlisted for some sport (e.g. staff or deregistered students), can result in the following messages. A possible correction for the errors is also given:
- Table Ref STUDS undefined! (change STUDS to STUDENTS)
- SubQuery must result in a single column! (remove "NUMBER, ")
- Types are not comparable! (change NAME to NUMBER)
- OK

[X]

A useful function for checking a comparison predicate like "A + 4 > 5.0" is comparable(VE_EDP, VE_EDP) -> ERROR.
Given two results from typechecking value expressions, i.e. two tuples <ERROR, DTDescr>, this function determines as output (see equations [comp1] - [comp8]):
- an error message when either one or both operands are incorrect, or
- an error "Types are not comparable!", when this is the case, or
- "OK" when both operand are correct and comparable.

The message OK is returned when both operands are correctly typed and the function comparable(DTDescr, DTDescr) -> BOOL returns true. Note that the latter reduces to "true" for all the cases for which both datatypes are comparable. For all (11) other cases no equation is given, so they are in normal form already. Therefore we need to test for "comparable() != true" instead of "comparable() = false".

Examples 7 (omitting parameters _EnvDescr and _TVListDescr)
```
pred-check(SPORT = 'Zwemmen') -> [pred1]
```

comparable(ve-check(SPORT), ve-check('Zwemmen')) -> (see TC_ValueExpr)
comparable(<OK, <String, 10, 0>>, <OK, <String, 7, 0>>) -> [comp3]
OK
The last reduction because the condition succeeds:
comparable(<String, 10, 0>, <String, 7, 0>) = true -> [comp4]
true = true.

pred-check(SPORT = 4)
would result in (see [comp2]):
Types are not comparable!
since there are no equations applicable for comparable(<String, 10, 0>, <Exact, 1, 0>).

pred-check(NEAR = FAR)
would result in (see [comp1]):
Column NEAR undefined! AND Column FAR undefined!
since the check of both value expressions (column references) will return non-OK errors.
[X]

The typecheck of a like predicate (equation [pred10]) is a nice example of the use of "AND" and "AND THEN" for errors.

Example 8 (again omitting some parameters)
pred-check(NAME LIKE 4 ESCAPE '\') -> [pred10]
must-be-string(NAME) AND must-be-string(4) AND
(must-be-string('\') AND THEN must-be-length1('\')) ->
OK AND Type of 4 must be a string! AND
(OK AND THEN Value '\' must be a single char!) ->
Type of 4 must be a string! AND Value '\' must be a single char!
[X]

TC_Query_sem
Checking a query specification:

SELECT SelectList
FROM {TableRef ","}+
WHERE SearchCondition
GROUP BY {ColumnSpec ","}+
HAVING SearchCondition

is the task of function query-check(EnvDescr, QuerySpec) -> QUERY_EDP and subsequent 'deeper' functions.

In very general terms the checking process is as follows:

1. texpr-check(EnvDescr, TVListDescr, TableExpr) -> TEXPR_EDP
Checks the table expression (starting at keyword FROM in the query) in the way described below. The second argument of this function is a list of tables, possibly from a preceding subquery and is used to determine if a column specification is an outer reference or not (as defined in §5.7 <column specification> Syntax Rules 4). For a start query-check() will provide an empty table list to this function.

a. from-check(EnvDescr, FromClause) -> FROM_EDP
using table-check(EnvDescr, TableReference) -> TABLE_EDP
Checks all tables mentioned in the from clause (FROM {TableRef ","}+) for their unambiguous presence in the environment, possibly renamed by a correlation name via correname() from module SchemaDescr.

Due to §5.20 <from clause> Syntax Rules 1, a correlation name will always replace the original table name. Therefore "SELECT * FROM R R1 WHERE R.C <> 0" will result in an error since R.C is an undefined column name. When all table references are considered OK, from-check() returns a description list of these tables.

b. where-check(EnvDescr, TVListDescr, WhereClause) -> WHERE_EDP
using search-check(EnvDescr, TVListDescr, SearchCondition) -> SEARCH_EDP
Checks the where clause (WHERE SearchCondition), i.e. all the containing predicates. Since column references in these predicates may refer to tables of the immediate preceding from clause, or to tables before that, a combination of the table lists is used for lookup; see function combine-tables() and Figure 4 below.

c. group-check(TVListDescr, GroupByClause) -> GROUP_EDP
Checks for correct use of containing column references in the group-by clause (GROUP BY {ColumnSpec ","}+) using the table list from the preceding from clause (and not the combined table list).

d. having-check(EnvDescr, TVListDescr, HavingClause) -> HAVING_EDP
Checks the containing search condition in the having clause (HAVING SearchCondition), using the combined table list.

The result of from-check() is a combined error from the typecheck functions mentioned in a. - d. and the table list from the containing from clause.

2. sell-check(EnvDescr, TVListDescr, SelectList) -> SELL_EDP
Checks the select list ("*" or one or more value expressions) in the context of the previously checked table expression (the table list resulting from that function). If a list of value expressions is specified each in turn is typechecked using ve-check() and, when no error is detected, the result is a list of column descriptions (named with special column name "_", not available to users). If "*" is specified a list of column descriptions is assembled of all column names and types from the tables given in the from clause. This list of column descriptions is used to expand the query specifications in the definition of a view and to determine the cardinality and type of a subquery (see functions subval-check() and column-check() of module TC_Pred_sem).

The passing of various table lists, and so implementing the scope rules (see also §5.20 <from clause> Syntax Rules 1 - 4), is shown in Figure 4:

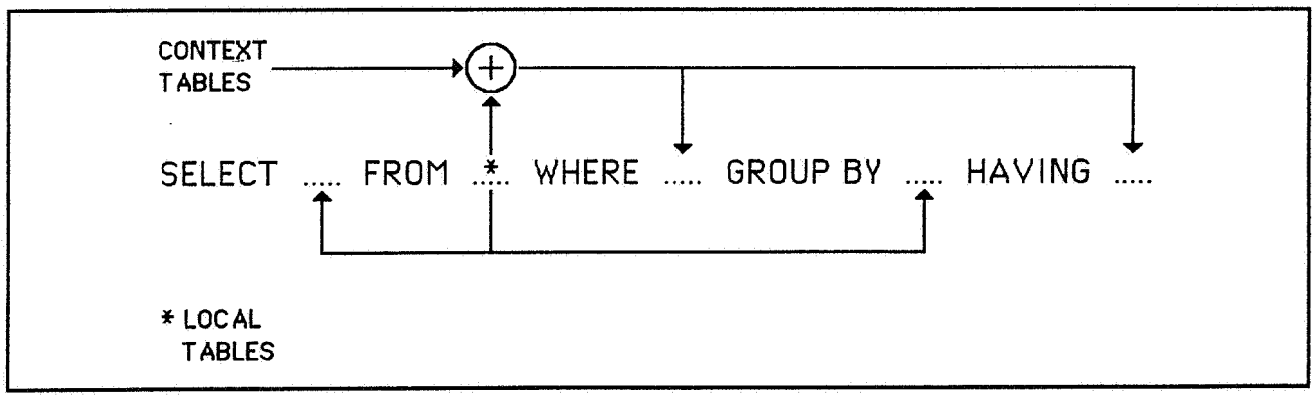

Figure 4: Passing table lists while checking a QuerySpec.

Example 9
Define E as the description of the environment of the sample database (see also Example 1 of this chapter) and S and M as the description of the tables STUDENTS resp. MEMBERS.
Further, define Q as the following query:

```
SELECT NAME FROM STUDENTS WHERE EXISTS
  (SELECT NUMBER FROM MEMBERS WHERE
   STUDENTS.NUMBER = MEMBERS.NUMBER AND
   MEMBERS.SPORT = 'Zwemmen')
```

We will demonstrate the typechecking of this query as follows:

```
query-check(E, Q) -> [query3]
<OK AND THEN OK, X, [<NAME, <String, 20, 0>, NULL, [], false>]>
```

So Q can be considered type-correct. When necessary, we can extract type information about the result of this query using the column descriptions (e.g. number, name and type of the column).

To show the rewriting of this typecheck function, we need quite a lot intermediate results:

1) from-check(E, FROM MEMBERS) -> [from1] via [table1] and using lookup-table()
   <OK, [M]>

2) combine-tables([M], [S]) -> [comb1]
   [S M]

3) search-check(E, [S M], STUDENTS.NUMBER = MEMBERS.NUMBER) -> [surch4]
   pred-check(E, [S M], STUDENTS.NUMBER = MEMBERS.NUMBER) -> [pred1]
   comparable(ve-check([S M], STUDENTS.NUMBER), ve-check(MEMBERS.NUMBER)) ->
   OK

4) search-check(E, [S M], MEMBERS.SPORT = 'Zwemmen') -> [surch4] & [pred1]
   comparable(ve-check([S M], MEMBERS.SPORT), ve-check('Zwemmen')) ->
   OK

5) using 3) & 4)
   search-check(E, [S M], BoolTerm AND BoolFactor) -> [surch2]
   <OK AND OK, > ->
   <OK, >

6) using 5)
   where-check(E, [S M], WHERE BoolTerm AND BoolFactor) -> [where1]
   <OK, >

7) using 1) and 6)
   texpr-check(E, [S], FROM MEMBERS WHERE SearchCond) -> [texpr4]
   <OK AND THEN OK, [M]> ->
   <OK, [M]>

(Note that [S M] can serve as context for the search condition, but only [M] is passed as a result to form the context for the preceding select list.)

8) using 7)
   sell-check(E, [M], NUMBER) -> [sell1]
   <OK, [<NUMBER, <Exact, 6, 0>, NULL, [], false>]>

(Since 7) gave us [M] as context for the select list, NUMBER is an unambiguous reference to a column of MEMBERS.)

9) using 7) and 8)
   subq-check(E, [S], (SELECT NUMBER FROM MEMBERS WHERE SearchCond)) -> subq3
   <OK AND THEN OK, X, [<NUMBER, <Exact, 6, 0>, NULL, [], false>]>

(The last item in the result tuple is a list column descriptions, telling us that the result of the subquery is a table consisting of a single column. This sole column has characteristics (e.g. name and type) as can be seen in the column description.)

10) using 9)
search-check(E, [S], EXISTS SubQuery) -> [surch4]
<pred-check(E, [S], EXISTS SubQuery, > -> [pred17]
<OK, >

11) using 10)
where-check(E, [S], WHERE EXISTS SubQuery) -> [where1]
<OK, >

12) from-check(E, FROM STUDENTS) -> [from1] via [table1] and using lookup-table()
<OK, [S]>

13) combine-tables([S], []) -> [comb1-2]
[S]

14) using 11), 12), and 13)
texpr-check(E, [], FROM STUDENTS WHERE EXISTS SubQuery) -> [texpr4]
<OK AND THEN OK, [S]>

15) sell-check(E, [S], NAME) -> [sell1]
<OK, [<NAME, <String, 20, 0>, NULL, [], false>]>
(We use the fact that ve-check([S], NAME) -> <OK, <string, 20, 0>>)

16) using 14) and 15)
query-check(E, Q) -> [query3]
<OK AND THEN OK, X, [<NAME, <String, 20, 0>, NULL, [], false>]>
X

Note: In the typecheck process above, all checks are performed in the conditions of the relevant equations, before the total error message is determined at the right hand side of the equation. This is rather inefficient when some error is detected at an early stage, since in many situations no more typechecking is relevant and thrown away anyway by the AND THEN construct. An alternative is to check the conditions sooner and then to decide to continue typechecking or not.

TC_QueryPred
• the main typecheck function tc(EnvDescr, QuerySpec) -> ERROR

This is simply a projection of the result of query-check() for use as top-level typechecking, for instance for checking a view definition or a query given by an end-user. Once an environment is converted to an EnvDescr (and checked OK), subsequent query specifications typed by an end-user can be typechecked using this function.

Example 10
Consider E and Q defined in the previous example, then
tc(E, Q) -> [tc1]
OK
X

Typecheck
The total typecheck function of query specifications: tc(Environment, QuerySpec) -> ERROR, which converts and checks an environment and checks the query specification accordingly.

5 Semantics of SQL

In this chapter we illustrate the meaning of SQL schema's and query specifications. For this purpose we have implemented translation functions from SQL to RDBS and so we are able to express SQL clauses in terms of relational databases and the relational algebra. Also, once we have a translated SQL schema and a proper database, we can execute SQL queries about these databases (i.e. reduce translated queries in module RDBS).

Note: since not all of the functionality of the SQL language has equivalents in the RDBS language, only a limited subset of SQL can be translated.

The translation functions are divided over three modules TR_Schema, TR_ValueExpr, and TR_QueryPred with import relations as shown in Figure 5.

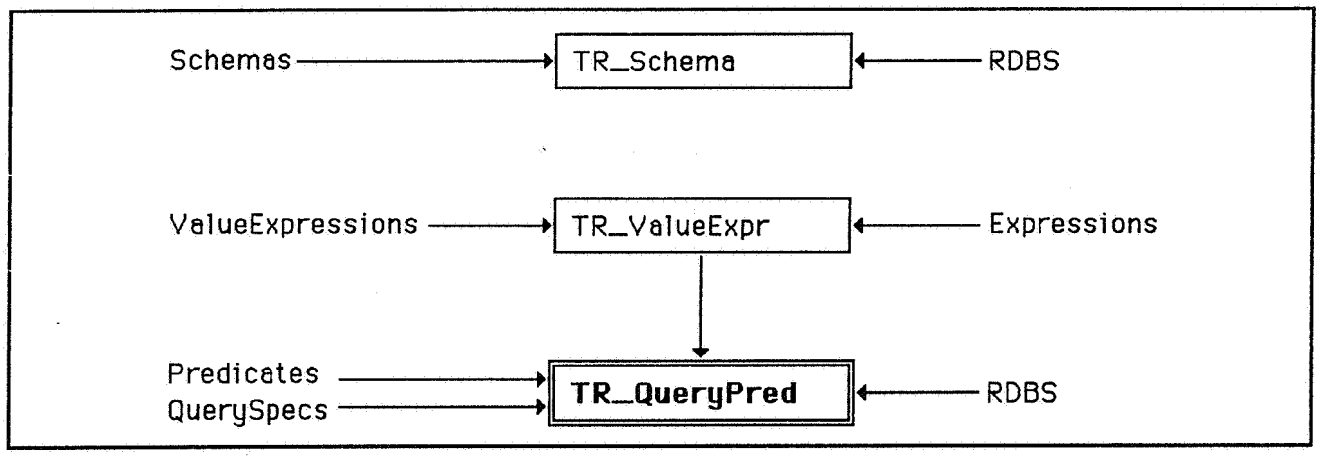

Figure 5: Importgraph of translation modules.

We will discuss each of the translation modules in turn:

TR_Schema
Main function is the translation of an SQL Schema to an RDBS SCHEMA using function tr(Schema) -> SCHEMA. This translation is quite straightforward: each table- and view definition in the schema is converted to a relation definition (RDEF) with attributes and corresponding domains.

Example 1

```
tr(CREATE TABLE STUDENTS (
   NUMBER  NUMERIC(6,0)
   NAME    CHAR(20)
   PHONE   CHAR(15)
))
->
schema
  STUDENTS <= {<NUMBER,NAME,PHONE> @ Integers#Strings#Strings}
```

X

Example 2

```
tr(CREATE VIEW SWIMMERS AS
   SELECT NAME FROM STUDENTS, MEMBERS
   WHERE STUDENTS.NUMBER = MEMBERS.NUMBER
   AND   MEMBERS.SPORT = 'Zwemmen'
)
->
schema
```

```
SWIMMERS <= {<NAME> @ Strings}
```
(Note: the view definition must also be converted to an expression in the database part of an RDBS schema/database/program triplet.)
[X]

Note: of course it would have been better if we had specified a translation function for an environment description.

TR_ValueExpr:
The translation of a value expression in SQL to an expression in RDBS is performed by the function tr(ValueExpr) -> EXPR. Again, only a limited subset of SQL's value expressions have a counterpart in RDBS. For instance variables, parameters, set functions, and grouping cannot be dealt with.

Example 3
```
tr(AMOUNT * 1.10) -> [ve3]
tr(AMOUNT) * tr(1.10) -> [ve4] & [ve11]
AMOUNT * 1.10
```
[X]

TR_QueryPred
Function tr(QuerySpec) -> REL converts an SQL query, and all language clauses that can occur in a query (including predicates), to a relational expression in RDBS.
Predicates are translated using function tr(Predicate) -> EXPR.

Examples 4 (see also the examples of predicates in §2.2):
```
tr(NUMBER = 901274) -> [pred1]
tr(NUMBER) = tr(901274) ->
NUMBER = 901274

tr(NUMBER BETWEEN 900000 AND 909999) -> [pred4]
(tr(NUMBER) >= tr(900000)) &(tr(NUMBER) <= tr(909999)) ->
(NUMBER >= 900000) &(NUMBER <= 909999)

tr(SPORT IN 'Tennis', 'Voetbal') -> [pred6] & [pred7]
(tr(SPORT) = tr('Tennis')) | (tr(SPORT) = tr('Voetbal')) ->
(SPORT = 'Tennis) | (SPORT = 'Voetbal')

tr(AMOUNT IS NULL) -> [pred14]
tr(AMOUNT) = null ->
AMOUNT = null

tr(NUMBER <= ALL (SELECT NUMBER FROM STUDENTS)) -> [pred16]
for_all <x> @ tr((SELECT NUMBER FROM STUDENTS)):x >= tr(NUMBER) ->
for_all <x> @ {<NUMBER> <- @ STUDENTS} : x >= NUMBER

tr(NUMBER <> ANY (SELECT NUMBER FROM MEMBERS)) -> [pred16]
tr(NUMBER <> SOME (SELECT NUMBER FROM MEMBERS)) -> [pred16]
there_is <x> @ tr((SELECT NUMBER FROM MEMBERS)):x <> tr(NUMBER) ->
there_is <x> @ {<NUMBER> <- @ MEMBERS} : x <> NUMBER

tr(EXISTS (SELECT * FROM MEMBERS)) -> [pred17]
# tr((SELECT * FROM MEMBERS)) ->
# {@ MEMBERS | true}
```
[X]

6 Conclusions

In this paper we have described a formal specification of the database language SQL. Its syntax is given in the corresponding SDF syntax modules. The static semantics of SQL schemas and queries is, at least for a large part, specified by means of an implemented typecheck function. The dynamic semantics of SQL queries which have a meaning in the relational algebra, is described by a translation function from this subset of SQL to a defined and implemented relational database language RDBS.

For this specification of SQL we used ASF+SDF as a formal method instead of the usual definitions in natural language. Thereby the following objectives were kept in mind:
- the relational databases defined and manipulated by the SQL language, are defined using the relational algebra in the same way as we would have done this without keeping SQL in mind, and
- the specification of SQL's syntax, typecheck rules and semantic translation had to follow the definition given in the standard (BNF, syntax rules, resp. general rules) as close as possible.

The most interesting issues which appeared during this specification process were the following:

- The definition of values and expressions:
  We defined values as the union of sorts describing basic datatypes, and expressions were based on the union of these sorts and variables. Other approaches than the one described here, led to either many undesired ambiguities or a less clear definition of basic datatypes. The major drawback of our approach is that it is time-consuming to incorporate a new datatype.

- Relational algebra instead of relational calculus:
  Most database queries demand logically the evaluation of the Cartesian product of two or more sets. It is very time- and space- consuming to make this evaluation explicit. For this reason, and some others as well, the relational calculus has been defined. This method, which has been proved to have the same power as relational algebra, defines set operations in terms of cursors. Just like SQL cursors, these range over the tuples occurring in some relation (or table).
  We have chosen to implement the relational algebra since this is much more easy than specifying relational calculus, especially using a functional method. To avoid the inefficiency mentioned, we have tried to define the relational operators in terms of
  head(RELATION) -> TUPLE and
  tail(RELATION) -> RELATION,
  the former giving some tuple of a relation and the latter giving the relation without the same tuple. This experiment has been very interesting, but resulted in such an increase in the number of equations that we had to drop it.

- BNF vs. SDF:
  The conversion of BNF to SDF in a straightforward way has been studied briefly to meet the requirement of keeping close to the original syntax definition of SQL in (extended) BNF. On the other hand we defined the relational database language RDBS in the usual way, more like a traditional algebraic specification. See for example the difference in the definition of expressions in both languages (EXPR resp. ValueExpr).
  Afterwards we regret the choice to define the syntax of SQL based on the BNF definition without much modification, since this leads to many unnecessary subsorts and thus to an enormous overhead for the parser. However, subsorts are practical from time to time to reduce the number of cases to be dealt with in the equations.

- Choices made for typechecking:
  - a datatype for the description of an environment (comparable to a symbol table in compilers),
  - simple yet adequate error messages are returned by the typecheck functions,
  - no translation during typecheck is done, but only afterwards and straightforward,
  - views are expanded to base table definitions, after the schema's are typechecked successfully (compare with the problem of expressions in declarations), and
  - passing table lists fulfilling the scope rules for tables and columns in queries (outer references).
  These topics have been discussed in section 4.3 already and will not be repeated here.

- Grouping and set functions:
  As mentioned in the introduction, many claim that SQL is incomprehensive. For a large part this has to do with the grouping mechanism of SQL and the consequences it has on the allowed results of a query. For example (table R has columns A and B):
  SELECT A, COUNT(B) FROM R GROUP BY A HAVING COUNT(B) > 0
  Without the group by- and having clauses, the SelectList would have been wrong. Due to lack of time we were not able to incorporate these checks in the typecheck function.

Now for the results of this project. In the first place we consider it a success, but only a partial success. Indeed it is theoretically and practically possible to define a language like SQL using a formal method. A designer of an SQL compiler can use such a complete specification as a basis for his/her design. On the other hand this is probably the maximum gain we get from this method. The specifications listed in the appendices are not very clear to read (sometimes not even for myself after some time, I must admit). So we will not claim this specification can be exchanged with the original standard.

The total amount of work that has been done during my training is not as much as I hoped for beforehand. There were a number of counterforces, of which we list:

- Specifying a language like SQL top-down by someone who is inexperienced with algebraic specifications or functional programming, is a bit naive. Working the other way, bottom-up starting with basic datatypes, expressions, relations and the relational algebra, has proven to be a more fruitful approach. However implementing the needed datatypes ourselves, instead of using predefined libraries or hybrid specifications, took too much time.

- The syntax formalism is still a bit low-level in the sense of not having optional- and alternative constructions in syntax definitions and because the equations require a lot of cases to be written out in full. When specifying a language like Pascal one may not be aware of this, but SQL has a lot of these syntax constructions. Therefore changing the syntax or even the name of a variable takes a lot of time.

7. Personal comments about the ASF+SDF system

In this chapter I would like to express some comments/thoughts concerning the formalism and the system, i.e. the meta-system of ASF+SDF.

First a preliminary remark should be made: the system is not a finished product, it is still evolving: bugs are prepared, problems solved, features added, etc. Even during my training many changes have been made. The most striking example is the additions of the 'hybrid' feature, see [9]. In first instance I left out the datatype REAL from the specification, because this would result in too much work (difficult syntax, many equations, etc). Because of this evolutionary process it is possible that some of my comments are obsolete or premature.
Another remark is that most of my comments are either about syntactic sugar, or about the user interface. In both cases it is not always wanted just to add all the features a user requests.

The remarks are divided into sections, each concerning the sub-system or facility mentioned.

1. Lexical syntax:
- the formalism lacks grouping of lexical objects:
  when a-d are lexical notions, then so should be: a(bc)*d,
- the formalism lacks alternatives of lexical objects:
  when a-d are lexical notions, then so is a(b|c)d,
- the formalism lacks optional constructs:
  example: NAT ("." NAT)? ("E" ("+" | "-")? NAT)? -> REAL
  example (definition of quotes inside a quoted string): "\" (~[\] | "\\")* "\".

2. Context-free syntax:
- especially when defining languages it is more convenient to write down and use a BNF grammar than SDF. This has only to do with the direction of a context-free rule. This results in BNF-format in a more readable layout, because there is more layout possible. Looking for a nonterminal in the left margin is more practical in BNF:

Example 1

```
BNF-format
   Statement ::=
      if <Expression> then <Statements> [ else <Statements> ] fi ;
      | while <Expression> do <Statements> od ;
      | begin <Statements> end ;
SDF-format
   "if" Expression "then" Statements "fi" ";"                    -> Statement
   "if" Expression "then" Statements "else" Statements "fi" ";"  -> Statement
   "while" Expression "do" Statements "od" ";"                   -> Statement
   "begin" Statements "end" ";"                                  -> Statement
```

X

So perhaps it is possible to have a context-free function also defined as:
Id "<-" LexElem+,
- as can be seen in the example above, also an alternative could be practical,
- grouping without subsort:
  "A (BC)* D -> S" instead of "A T* D -> S BC -> T",
- an optional construct would make certain specifications more clear:
  "SELECT" ("ALL" | "DISTINCT")? SelectList TableExpr -> QuerySpec,

- ambiguities caused by injections of sorts into one another should be resolved using a clear mechanism. For example the expression 4 + 2 has two interpretations (INT "+" INT -> INT or REAL "+" REAL -> REAL) when an integer constant is defined as a real constant as well (e.g. INT -> REAL, INT "." INT -> REAL). I would prefer this expression to be treated as an INT expression by default and as a REAL expression when the priority REAL "+" REAL -> REAL > INT "+" INT -> INT (or REAL > INT) is given in the priorities section.

3. Modularity:
- it should be possible to restrict imported and especially exported signatures,
- it should be possible to split up the equations logically belonging to a single syntax specification, into two or more equations sections; combining semantics to syntax should preferably be done in the imports specification. Sometimes only a part of the syntax c.q. semantics is needed. In the first case we can restrict the imported syntax using restricted imports, the latter should be possible too,
- the name of a module should be part of the module syntax; using the name of the file on which a module can be found as module name, is not an elegant choice,
- empty sections should be allowed; it is annoying to have to remove 'lexical syntax' when there are no lexical functions or to remove 'equations' when we want to comment out some equations temporary,
- cyclic imports caused by dividing a specification into two or more modules should be possible.

4. Meta-system:
- mapping of modules (syntax plus semantics) to filenames and vice versa, should be a specification of its own,
- asking a user to save changes made to a text should be done before the window is closed.

5. Variables:
- the flexible declaration of variables is excellent.

6. Equations:
- I don't like tags, I dislike their syntax,
- meta-syntax for equations can be defined to ease the problem of dealing with many cases, e.g. some sort of case construct for the result of an equation:

Example 2

```
_Expr1 + _Expr2 =
CASE
    type(_Expr1) = integer & type(_Expr2) = integer  ==> add-int(_Expr1, _Expr2)
    type(_Expr1) = integer & type(_Expr2) = real     ==> add-real(itor(_Expr1), _Expr2)
    type(_Expr1) = real & type(_Expr2) = integer     ==> add-real(_Expr1, itor(_Expr2))
    type(_Expr1) = real & type(_Expr2) = real        ==> add-real(_Expr1, _Expr2)
    DEFAULT                                          ==> ERROR!
END
```

X

- the order of equations tried to reduce a term should either be defined (first rule first, lowest tag first, or whatever) or intentionally random. The situation as it is now (first rule first, but not guaranteed) is too tempting for not anticipating on the order of evaluation,
- many language constructs consist of lists (or optionals), so in many situations we have to deal with the cases empty vs. non-empty. An empty list (or optional) is a syntactically difficult object, because it is literally empty. The usual solution is to surround a list by opening- and closing brackets (e.g. {/} or begin/end). Especially for an optional defined as a subsort of its own, it should be possible to express the case that the optional is empty, as given in the following example:

Example 3

```
"procedure" OptArgList ";"   -> ProcDecl
"(" ArgList ")"              -> OptArgList
% empty %                    -> OptArgList
```

```
{ Arg ","}+                    -> ArgList
[..] tc(procedure _OptArgList;) = tc(_OptArgList)
[..] _OptArgList = ( ArgList ) ==> tc(_OptArgList) = tc(ArgList)
[..] _OptArgList = %empty% ==> tc(_OptArgList) = OK
```
X

- the choice for the symbol "=" to indicate the fact that left-hand side equals right-hand side in an equation, is obvious for logical and historical reasons; it should be possible however to use another symbol (like "-->") when we want to specify a function S "=" S -> BOOL of our own,
- in many cases it is convenient to consider conditions as boolean conditions. I do not suggest that booleans should be incorporated in the ASF+SDF formalism. However, an operator resembling boolean "or" (just like "," resembles much to boolean "and") would be a nice-to-have feature as can be seen in the following example:

Example 4

```
[..] type(e1) = real | type(e2) = real ==> e1 + e2 = real-addition(e1, e2)
```
X

7. Reductions:
- also as a debugging facility it would be nice to have a reduction of the contents of the focus alone, e.g. tc(descr(schema), query) --reduce--> tc(envdescr, query); preferably in the same window (so replacing the subterm in the focus by its normal form),
- another useful feature would be the possibility to have the result of a reduction be written in a separate output window; an input window for 'user' entries would likewise be thrilling.

8. Debugger:
The debug facility EDB, as described in [12], has been used frequently. A later version of this debugger was not quite suited for my application (because of the very large terms), so I used it less than before. I personally would prefer to have a window containing a term to be reduced, a selection of a subterm to be rewritten next (with a message which equation is going to be used) and a set of menus and buttons for controlling this rewriting. After the, say, 'step'-button, the selected subterm is then to be replaced by another term. So after repeatedly pressing this button, or otherwise, the total rewriting process can be simulated visually. The level of detail of the rewriting should be limited, for instance: show reductions of the current module in detail and only show the results of reductions of other modules. Testing conditions can be done in newly created windows, depending on some level set by the user. E.g. some level only shows reductions (and eventually success or failure of conditions) and yet another level shows reductions of a condition in another window.

9. Editor:
- using the power of ASF+SDF it would be nice to have a find/replace facility, for instance: change the name of the function INT + INT -> INT to function int-add(INT, INT) -> INT. Applying this replace to a context-free function definition, this could result in changing some or all equations where this function occurs,
- the permanent display of the sortname of current focus, instead of using the expand menu, would be practical for inspecting terms in a language,
- it should be possible to position the cursor using a mouseclick without parsing,
- it is understandable, but still annoying, that zooming out should lead to a parse.

10. Miscellaneous:
- pretty print: too soon is chosen for a vertical layout for list structures; large terms (like a RDBS program for instance) become soon unreadable,
- using the disambiguator (dialog window showing the possible parsetrees of a subterm) should be avoided as much as possible (there must be at least a possibility to interrupt the current parse). I would like to have a default choice mechanism for each ambiguity possible; this method, and the way to overrule it, should be obvious to the average user.

8 References

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Appendix A: BNF grammar definition of SQL

5. Common elements

5.1 <character>

```
<character> ::= <digit> | <letter> | <special character>
<digit> ::= 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
<letter> ::= <upper case letter> | <lower case letter>
<upper case letter> ::=
    A | B | C | D | E | F | G | H | I
  | J | K | L | M | N | O | P | Q | R
  | S | T | U | V | W | X | Y | Z
<lower case letter> ::=
    a | b | c | d | e | f | g | h | I
  | j | k | l | m | n | o | p | q | r
  | s | t | u | v | w | x | y | z
<special character> ::=
  See Syntax Rule 1.
```

5.2 <literal>

```
<literal> ::= <character string literal> | <numeric literal>
<character string literal> ::= ' <character representation>... '
<character representation> ::= <nonquote character> | <quote representation>
<nonquote character> ::= See Syntax Rule 1.
<quote representation> ::= "
<numeric literal> ::= <exact numeric literal> | <approximate numeric literal>
<exact numeric literal> ::=
    [+|-] <unsigned integer>[. <unsigned integer>]
  | [+|-] <unsigned integer> .
  | [+|-] . <unsigned integer>
<approximate numeric literal> ::= <mantissa>E<exponent>
<mantissa ::= <exact numeric literal>
<exponent> ::= <signed integer>
<signed integer> ::= [+|-]<unsigned integer>
<unsigned integer> ::= <digit>...
```

5.3 <token>

```
<token> ::= <nondelimiter token> | <delimiter token>
<nondelimiter token> ::= <identifier> | <keyword> | <numeric literal>
<identifier> ::= <upper case letter> | [{<underscore>|<letter or digit>}...]
<underscore> ::= _
<letter or digit> ::= <upper case letter> | <digit>
<keyword> ::=
    ALL | AND | ANY | AS | ASC | AUTHORIZATION | AVG
  | BEGIN | BETWEEN | BY
  | CHAR | CHARACTER | CHECK | CLOSE | COBOL | COMMIT
  | CONTINUE | COUNT | CREATE | CURRENT | CURSOR
  | DEC | DECIMAL | DECLARE | DEFAULT | DELETE | DESC | DISTINCT | DOUBLE
  | END | ESCAPE | EXEC | EXISTS
  | FETCH | FLOAT | FOR | FOREIGN | FORTRAN | FOUND | FROM
  | GO | GOTO | GRANT | GROUP | HAVING
  | IN | INDICATOR | INSERT | INT | INTEGER | INTO | IS
  | KEY | LANGUAGE | LIKE
  | MAX | MIN | MODULE | NOT | NULL | NUMERIC
  | OF | ON | OPEN | OPTION | OR | ORDER
  | PASCAL | PLI | PRECISION | PRIMARY | PRIVILEGES | PROCEDURE | PUBLIC
  | REAL | REFERENCES | ROLLBACK
  | SCHEMA | SECTION | SELECT | SET | SMALLINT | SOME
  | SQL | SQLCODE | SQLERROR | SUM
  | TABLE | TO | UNION | UNIQUE | UPDATE | USER
  | VALUES | VIEW | WHENEVER | WHERE | WITH | WORK
```

```
<delimiter token> ::= <character string literal>
   | , | ( | ) | < | > | . | : | = | * | + | - | / | <> | >= | <=
<separator> ::= {<comment> | <space> | <newline>}...
<comment> ::= --[<character>...]<newline>
<newline> ::= implementor-defined end-of-line indicator
<space> ::= space character

5.4 Names
<table name> ::= [<authorization identifier>.]<table identifier>
<authorization identifier> ::= <identifier>
<table identifier> ::= <identifier>
<column name> ::= <identifier>
<correlation name> ::= <identifier>
<module name> ::= <identifier>
<cursor name> ::= <identifier>
<procedure name> ::= <identifier>
<parameter name> ::= <identifier>

5.5 <data type>
<data type> ::=
     <character string type>
   | <exact numeric type>
   | <approximate numeric type>
<character string type> ::= CHARACTER[(<length>)] | CHAR[(<length>)]
<exact numeric type> ::=
     NUMERIC[(<precision>[,<scale>])]
   | DECIMAL[(<precision>[,<scale>])]
   | DEC[(<precision>[,<scale>])]
   | INTEGER
   | INT
   | SMALLINT
<approximate numeric type> ::=
     FLOAT[(<precision>)]
   | REAL
   | DOUBLE PRECISION
<length ::= <unsigned integer>
<precision ::= <unsigned integer>
<scale ::= <unsigned integer>

5.6 <value specification> and <target specification>
<value specification> ::=
     <parameter specification>
   | <variable specification>
   | <literal>
   | USER
<target specification> ::= <parameter specification> | <variable specification>
<parameter specification> ::= <parameter name>[<indicator parameter>]
<indicator parameter> ::= [INDICATOR]<parameter name>
<variable specification> ::= <embedded variable name>[<indicator variable>]
<indicator variable> ::= [INDICATOR]<embedded variable name>

5.7 <column specification>
<column specification> ::= [<qualifier>.]<column name>
<qualifier> ::= <table name> | <correlation name>
```

```
5.8 <set function specification>
<set function specification> ::=
     COUNT(*)
   | <distinct set function>
   | <all set function>
<distinct set function> ::=
   { AVG | MAX | MIN | SUM | COUNT}(DISTINCT <column specification>)
<all set function> ::=
   { AVG | MAX | MIN | SUM}([ALL] <value expression>)

5.8 <value expression>
<value expression> ::=
     <term>
   | <value expression> + <term>
   | <value expression> - <term>
<term> ::=
     <factor>
   | <term> * <factor>
   | <term> / <factor>
<factor> ::= [+|-]<primary>
<primary> ::=
     <value specification>
   | <column specification>
   | <set function specification>
   | (<value expression>)

5.10 <predicate>
<predicate> ::=
     <comparison predicate>
   | <between predicate>
   | <in predicate>
   | <like predicate>
   | <null predicate>
   | <quantified predicate>
   | <exists predicate>

5.11 <comparison predicate>
<comparison predicate> ::=
  <value expression> <comp op> {<value expression> | <subquery>}
<comp op> ::= = | <> | < | > | <= | >=

5.12 <between predicate>
<between predicate> ::=
  <value expression> [NOT] BETWEEN <value expression> AND <value expression>

5.13 <in predicate>
<in predicate> ::=
  <value expression> [NOT] IN {<subquery> | (<in value list>)}
<in value list> ::=
  <value specification> {,<value specification>}...

5.14 <like predicate>
<like predicate> ::=
  <column specification> [NOT] LIKE <pattern> [ESCAPE <esape character>]
<pattern> ::= <value specification>
<esape character> ::= <value specification>

5.15 <null predicate>
<null predicate> ::= <column specification> IS [NOT] NULL
```

```
5.16 <quantified predicate>
<quantified predicate> ::= <value expression> <comp op> <quantifier> <subquery>
<quantifier> ::= <all> | <some>
<all> ::= ALL
<some> ::= SOME | ANY

5.17 <exists predicate>
<exists predicate> ::= EXISTS <subquery>

5.18 <search condition>
<search condition> ::=
     <boolean term>
   | <search condition> OR <boolean term>
<boolean term> ::=
     <boolean factor>
   | <boolean term> AND <boolean factor>
<boolean factor> ::= [NOT] <boolean primary>
<boolean primary>  := <predicate> | (<search condition>)

5.19 <table expression>
<table expression> ::=
   <from clause>
   [<where clause>]
   [<group by clause>]
   [<having clause>]

5.20 <from clause>
<from clause> ::= FROM <table reference>[{,<table reference>}...]
<table reference> ::= <table name> [<correlation name>

5.21 <where clause>
<where clause> ::= WHERE <search condition>

5.22 <group by clause>
<group by clause> ::=
   GROUP BY <column specification>[{,<column specification>}...]

5.23 <having clause>
<having clause> ::= HAVING <search condition>

5.24 <subquery>
<subquery> ::= (SELECT [ALL|DISTINCT] <result specification><table expression>)
<result specification> ::= <value expression> | *

5.25 <query specification>
<query specification> ::= SELECT [ALL|DISTINCT] <select list><table expression>
<select list> ::= <value expression>[{,<value expression>}...] | *
```

6. Schema definition language

```
6.1 <schema>
<schema> ::=
   CREATE SCHEMA <schema authorization clause> [<schema element>...]
<schema authorization clause> ::=
   AUTHORIZATION <schema authorization identifier>
<schema authorization identifier> ::= <authorization identifier>
<schema element> ::=
     <table definition>
   | <view definition>
   | <privilege definition>
```

```
6.2 <table definition>
<table definition> ::=
   CREATE TABLE <table name> (<table element>[{,<table element>}...])
<table element> ::=
     <column definition>
   | <table constraint definition>

6.3 <column definition>
<column definition> ::=
   <column name> <data type> [<default clause>] [<column constraint>...]
<column constraint> ::=
     NOT NULL [<unique specification>]
   | <references specification>
   | CHECK(<search condition>)

6.4 <default clause>
<default clause> ::= DEFAULT {<literal>|USER|NULL}

6.5 <table constraint definition>
<table constraint definition> ::=
     <unique constraint definition>
   | <referential constraint definition>
   | <check constraint definition>

6.6 <unique constraint definition>
<unique constraint definition> ::=
   <unique specification> (<unique column list>)
<unique specification> ::= UNIQUE | PRIMARY KEY
<unique column list> ::= <column name>[{,<column name>}...]

6.7 <referential constraint definition>
<referential constraint definition> ::=
   FOREIGN KEY(<referencing columns>)
   <references specification>
<references specification> ::= REFERENCES <referenced table and columns>
<referencing columns> ::= <reference column list>
<referenced table and columns> ::= <table name>[(<reference column list>)]
<reference column list> ::= <column name>[{,<column name>}...]

6.8 <check constraint definition>
<check constraint definition> ::= CHECK(<search condition>)

6.9 <view definition>
<view definition> ::=
   CREATE VIEW <table name> [(<view column list>)]
   AS <query specification> [WITH CHECK OPTION]

6.10 <privilege definition>
<privilege definition> ::=
   GRANT <privileges> ON <table name>
   TO <grantee>[{,<grantee>}...]
   [WITH CHECK OPTION]
<privileges> ::=
     ALL PRIVILEGES
   | <action>[{,<action>}...]
<action> ::=
     SELECT | INSERT | DELETE
   | UPDATE [(<grant column list>)]
   | REFERENCES [(<grant column list>)]
<grant column list> ::=
   <column name> [{,<column name>}...]
<grantee> ::= PUBLIC | <authorization identifier>
```

7. Module language

7.1 <module>

```
<module> ::=
   <module name clause>
   <language clause>
   <module authorization clause>
   [<declare cursor>...]
   <procedure>...
```

7.2 <module name clause>

```
<module name clause> ::= MODULE [<module name>]
```

7.3 <procedure>

```
<procedure> ::=
   PROCEDURE <procedure name> <parameter declaration>...;
   <SQL statement>;
<parameter declaration> ::=
   <parameter name> <datatype>
   | <SQLCODE parameter>
<SQLCODE parameter> ::=
   SQLCODE
<SQL statement> ::=
     <close statement>
   | <commit statement>
   | <delete statement: positioned>
   | <delete statement: searched>
   | <fetch statement>
   | <insert statement>
   | <open statement>
   | <rollback statement>
   | <select statement>
   | <update statement: positioned>
   | <update statement: searched>
```

8. Data manipulation language

8.1 <close statement>

```
<close statement> ::= CLOSE <cursor name>
```

8.2 <commit statement>

```
<commit statement> ::= COMMIT WORK
```

8.3 <declare cursor>

```
<declare cursor> ::=
   DECLARE <cursor name> CURSOR FOR <cursor specification>
<cursor specification> ::=
   <query expression>[<order by clause>]
<query expression> ::=
   <query term>
   | <query expression> UNION [ALL] <query term>
<query term> ::=
   <query specification> | (<query expression>)
<order by clause> ::=
   ORDER BY <sort specification> [{, <sort specification>}...]
<sort specification> ::=
   {<unsigned integer> | <column specification>} [ASC | DESC]
```

8.4 <delete statement: positioned>

```
<delete statement: positioned> ::=
   DELETE FROM <table name> WHERE CURRENT OF <cursor name>
```

```
8.5 <delete statement: searched>
<delete statement: searched> ::=
   DELETE FROM <table name> [WHERE <search condition>]

8.6 <fetch statement>
<fetch statement> ::=
   FETCH <cursor name> INTO <fetch target list>
<fetch target list> ::=
   <target specification> [{, <target specification>}...]

8.7 <insert statement>
<insert statement> ::=
   INSERT INTO <table name> [(<insert column list>)]
   { VALUES (<insert value list>)|<query specification>}
<insert column list> ::=
   <column name> [{,<column name>}...]
<insert value list> ::=
   <insert value> [{,<insert value>}...]
<insert value> ::=
   <value specification> | NULL

8.8 <open statement>
<open statement> ::= OPEN <cursor name>

8.9 <rollback statement>
<rollback statement> ::= ROLLBACK WORK

8.10 <select statement>
<select statement> ::=
   SELECT [ALL | DISTINCT] <select list>
   INTO <select target list>
   <table expression>
<select target list> ::=
   <target specification>[{,<target specification>}...]

8.11 <update statement: positioned>
<update statement: positioned> ::=
   UPDATE <table name>
   SET <set clause: positioned>[{,<set clause: positioned>}...]
   WHERE CURRENT OF <cursor name>
<set clause: positioned> ::=
   <object column: positioned> = {<value expression> | NULL}
<object column: positioned> ::= <column name>

8.12 <update statement: searched>
<update statement: searched> ::=
   UPDATE <table name>
   SET <set clause: searched>[{,<set clause: searched>}...]
   [WHERE <search condition>]
<set clause: searched> ::=
   <object column: searched> = {<value expression> | NULL}
<object column: searched> ::= <column name>
```

```
module Layout

exports

  lexical syntax

    [ \t\n]                     -> LAYOUT
    "%%" ~[\n]* [\n]            -> LAYOUT
    "%" ~[%]* "%"               -> LAYOUT

  variables

    "_Char"[0-9']*              -> CHAR
    "_Char*"[0-9']*             -> CHAR*
    "_Char+"[0-9']*             -> CHAR+


end Layout


module Lisp

%%
%% The module LISP
%%
%% The EQM knows about this module.
%% DON'T EDIT, except when you want to add LispIds
%% to the lexical (not context-free!) syntax.
%%
%%
 * Not yet supported:
% ` and ,

exports
    sorts
        LISP
        %% hiddens
        LispAtom StringPart PackagePart QuotedLispAtom
        LispId LispString


lexical syntax
        %% All non control or meta characters that have characterclass pname.

        %% [$%&*+\-/0-9<=>?@A-Z\\_a-z~]+   -> LispAtom
        [A-Za-z0-9\-]+   -> LispAtom
        ":" LispAtom                    -> PackagePart
        "#" PackagePart+                -> LispId
        "#%"[01]+                       -> LispId
        "#$"[0-9a-fA-F]+                -> LispId
        "#^"[a-zA-Z@]                   -> LispId

        "|" ~ [|]* "|"                  -> QuotedLispAtom
        QuotedLispAtom+                 -> LispAtom

        LispAtom                        -> LispId

        "\"" ~["]* "\""                 -> StringPart
        StringPart+                     -> LispString

        %% ";" ~[\n]* "\n"                  -> LAYOUT

        [ \t\n]                         -> LAYOUT

context-free syntax

        LispId       -> LISP
        LispString   -> LISP

        "(" LISP * ")" -> LISP
%% And when you prefer them, they aren't prefered.
        "<<" Condition ">>" -> LISP
         "'" LISP -> LISP


end Lisp
```

```
module Booleans

imports

  Layout

exports

  sorts

    BOOL_CONST
    BOOL

  lexical syntax

    "true"                      -> BOOL_CONST
    "false"                     -> BOOL_CONST

  context-free syntax

    BOOL_CONST                  -> BOOL
    "!" BOOL                    -> BOOL
    BOOL "|" BOOL               -> BOOL { left }
    BOOL "&" BOOL               -> BOOL { left }
    "(" BOOL ")"                -> BOOL { bracket }
    BOOL "=" BOOL               -> BOOL { left }
    BOOL "<>" BOOL              -> BOOL { left }

  variables

    "_BoolConst"[0-9']*         -> BOOL_CONST
    "_Bool"[0-9']*              -> BOOL

priorities

    "!" BOOL -> BOOL >
    { left: BOOL "&" BOOL -> BOOL, BOOL "|" BOOL -> BOOL } >
    { left: BOOL "=" BOOL -> BOOL, BOOL "<>" BOOL -> BOOL }

equations

[not1]  !true  = false
[not2]  !false = true

[or1 ]  true  | _Bool = true
[or2 ]  false | _Bool = _Bool
[or3 ]  _Bool | true  = true
[or4 ]  _Bool | false = _Bool

[and1]  true  & _Bool = _Bool
[and2]  false & _Bool = false
[and3]  _Bool & true  = _Bool
[and4]  _Bool & false = false

[eq1 ]  _BoolConst1  = _BoolConst2 ==>
        (_BoolConst1 = _BoolConst2) = true
[eq2 ]  _BoolConst1 != _BoolConst2 ==>
        (_BoolConst1 = _BoolConst2) = false

[neq1]  _BoolConst1  = _BoolConst2 ==>
        (_BoolConst1 <> _BoolConst2) = false
[neq2]  _BoolConst1 != _BoolConst2 ==>
        (_BoolConst1 <> _BoolConst2) = true

end Booleans
```

```
module Integers

imports
  Layout Booleans

exports
  sorts
    DIGIT INT_CONST INT
  lexical syntax
    [0-9]                          -> DIGIT
    DIGIT+                         -> INT_CONST
  context-free syntax
    INT_CONST                      -> INT
    "+" INT                        -> INT
    "-" INT                        -> INT
    INT "+" INT                    -> INT  { left }
    INT "-" INT                    -> INT  { left }
    INT "*" INT                    -> INT  { left }
    INT "/" INT                    -> INT  { left }
    INT "$" INT                    -> INT  { left }
    "(" INT ")"                    -> INT  { bracket }

    INT "=" INT                    -> BOOL
    INT "<>" INT                   -> BOOL
    INT ">" INT                    -> BOOL
    INT "<" INT                    -> BOOL
    INT "<=" INT                   -> BOOL
    INT ">=" INT                   -> BOOL

    inc "(" INT ")"                -> INT
    dec "(" INT ")"                -> INT
    max "(" INT "," INT ")"        -> INT
    min "(" INT "," INT ")"        -> INT

  variables
    "_Digit"[0-9']*                -> DIGIT
    "_IntConst"[0-9']*             -> INT_CONST
    "_Int"[0-9']*                  -> INT
    "_Ints"[0-9']*                 -> { INT "," }*

hiddens

  sorts

    LIST

  context-free syntax

    INT "_" INT                    -> INT { left }
    "[" { INT "," }* "]"           -> LIST
    LIST "." DIGIT                 -> INT

priorities

    { "+" INT -> INT, "-" INT -> INT } >
    { left: INT "*" INT -> INT, INT "/" INT -> INT, INT "$" INT -> INT } >
    { left: INT "+" INT -> INT, INT "-" INT -> INT } >
    { INT "=" INT -> BOOL, INT "<>" INT -> BOOL,
      INT ">" INT -> BOOL, INT ">=" INT -> BOOL,
      INT "<" INT -> BOOL, INT "<=" INT -> BOOL }

equations

%% INT_CONST -> INT (lexical definition)
[norm1] int_const("0" _Char+) = int_const(_Char+)

%% +|- INT -> INT (unary operators)
[uplus1] + _Int = _Int
[umin1] -- _Int = _Int
[umin2] - 0 = 0

%% lookup auxilary function
[item0] [_Int0,_Ints].0 = _Int0
[item1] [_Int0,_Int1,_Ints].1 = _Int1
[item2] [_Int0,_Int1,_Int2,_Ints].2 = _Int2
[item3] [_Int0,_Int1,_Int2,_Int3,_Ints].3 = _Int3
[item4] [_Int0,_Int1,_Int2,_Int3,_Int4,_Ints].4 = _Int4
[item5] [_Int0,_Int1,_Int2,_Int3,_Int4,_Int5,_Ints].5 = _Int5
[item6] [_Int0,_Int1,_Int2,_Int3,_Int4,_Int5,_Int6,_Ints].6 = _Int6
[item7] [_Int0,_Int1,_Int2,_Int3,_Int4,_Int5,_Int6,_Int7,_Ints].7 = _Int7
[item8] [_Int0,_Int1,_Int2,_Int3,_Int4,_Int5,_Int6,_Int7,_Int8,_Ints].8 = _Int8
[item9] [_Int0,_Int1,_Int2,_Int3,_Int4,_Int5,_Int6,_Int7,_Int8,_Int9,_Ints].9 = _Int9

%% INT + INT -> INT (addition)
[plus0] int_const(_Char) + int_const("0") = [ 0, 1, 2, 3, 4, 5, 6, 7, 8, 9].digit(_Char)
[plus1] int_const(_Char) + int_const("1") = [ 1, 2, 3, 4, 5, 6, 7, 8, 9,10].digit(_Char)
[plus2] int_const(_Char) + int_const("2") = [ 2, 3, 4, 5, 6, 7, 8, 9,10,11].digit(_Char)
[plus3] int_const(_Char) + int_const("3") = [ 3, 4, 5, 6, 7, 8, 9,10,11,12].digit(_Char)
[plus4] int_const(_Char) + int_const("4") = [ 4, 5, 6, 7, 8, 9,10,11,12,13].digit(_Char)
[plus5] int_const(_Char) + int_const("5") = [ 5, 6, 7, 8, 9,10,11,12,13,14].digit(_Char)
```

```
[plus6] int_const(_Char) + int_const("6") = [ 6, 7, 8, 9,10,11,12,13,14,15].digit(_Char)
[plus7] int_const(_Char) + int_const("7") = [ 7, 8, 9,10,11,12,13,14,15,16].digit(_Char)
[plus8] int_const(_Char) + int_const("8") = [ 8, 9,10,11,12,13,14,15,16,17].digit(_Char)
[plus9] int_const(_Char) + int_const("9") = [ 9,10,11,12,13,14,15,16,17,18].digit(_Char)

[plus10] int_const(_Char+1 _Char1) + int_const(_Char+2 _Char2) =
         int_const(_Char+ _Char)
         when int_const(_Char1) + int_const(_Char2) = int_const(_Char* _Char),
              int_const(_Char+1) + int_const(_Char+2) + int_const("0" _Char*) =
              int_const(_Char+)
[plus11] int_const(_Char+1 _Char1) + int_const(_Char2) =
         int_const(_Char+ _Char)
         when int_const(_Char1) + int_const(_Char2) = int_const(_Char* _Char),
              int_const(_Char+1) + int_const("0" _Char*) =
              int_const(_Char+)
[plus12] int_const(_Char1) + int_const(_Char+2 _Char2) =
         int_const(_Char+ _Char)
         when int_const(_Char1) + int_const(_Char2) = int_const(_Char* _Char),
              int_const(_Char+2) + int_const("0" _Char*) =
              int_const(_Char+)
[plus13]   _IntConst1 + - _IntConst2 =   (_IntConst1 - _IntConst2)
[plus14] - _IntConst1 +   _IntConst2 =   (_IntConst2 - _IntConst1)
[plus15] - _IntConst1 + - _IntConst2 = - (_IntConst1 + _IntConst2)

%% INT - INT -> INT (subtraction)
[min0] _IntConst1 - _IntConst2 = _IntConst1 _ _IntConst2
       when _IntConst1 >= _IntConst2 = true
[min1] _IntConst1 - _IntConst2 = - (_IntConst2 _ _IntConst1)
       when _IntConst1 >= _IntConst2 = false
[min2]   _IntConst1 - - _IntConst2 =   (_IntConst1 + _IntConst2)
[min3] - _IntConst1 -   _IntConst2 = - (_IntConst1 + _IntConst2)
[min4] - _IntConst1 - - _IntConst2 =   (_IntConst2 - _IntConst1)

[min0] int_const(_Char) _ int_const("0") = [ 0, 1, 2, 3, 4, 5, 6, 7, 8, 9].digit(_Char)
[min1] int_const(_Char) _ int_const("1") = [19, 0, 1, 2, 3, 4, 5, 6, 7, 8].digit(_Char)
[min2] int_const(_Char) _ int_const("2") = [18,19, 0, 1, 2, 3, 4, 5, 6, 7].digit(_Char)
[min3] int_const(_Char) _ int_const("3") = [17,18,19, 0, 1, 2, 3, 4, 5, 6].digit(_Char)
[min4] int_const(_Char) _ int_const("4") = [16,17,18,19, 0, 1, 2, 3, 4, 5].digit(_Char)
[min5] int_const(_Char) _ int_const("5") = [15,16,17,18,19, 0, 1, 2, 3, 4].digit(_Char)
[min6] int_const(_Char) _ int_const("6") = [14,15,16,17,18,19, 0, 1, 2, 3].digit(_Char)
[min7] int_const(_Char) _ int_const("7") = [13,14,15,16,17,18,19, 0, 1, 2].digit(_Char)
[min8] int_const(_Char) _ int_const("8") = [12,13,14,15,16,17,18,19, 0, 1].digit(_Char)
[min9] int_const(_Char) _ int_const("9") = [11,12,13,14,15,16,17,18,19, 0].digit(_Char)

[min10] int_const(_Char+1 _Char1) _ int_const(_Char+2 _Char2) =
        int_const(_Char+ _Char)
        when int_const(_Char1) _ int_const(_Char2) = int_const(_Char* _Char),
             int_const(_Char+1) _ int_const(_Char+2) _ int_const("0" _Char*) =
             int_const(_Char+)
[min11] int_const(_Char+1 _Char1) _ int_const(_Char2) =
        int_const(_Char+ _Char)
        when int_const(_Char1) _ int_const(_Char2) = int_const(_Char* _Char),
             int_const(_Char+1) _ int_const("0" _Char*) =
             int_const(_Char+)
[min12] int_const(_Char1) _ int_const(_Char+2 _Char2) =
        int_const(_Char+ _Char)
        when int_const(_Char1) _ int_const(_Char2) = int_const(_Char* _Char),
             int_const(_Char+2) _ int_const("0" _Char*) =
             int_const(_Char+)

%% INT * INT -> INT (multiplication)
[time0] int_const(_Char) * int_const("0") = [ 0, 0, 0, 0, 0, 0, 0, 0, 0, 0].digit(_Char)
[time1] int_const(_Char) * int_const("1") = [ 0, 1, 2, 3, 4, 5, 6, 7, 8, 9].digit(_Char)
[time2] int_const(_Char) * int_const("2") = [ 0, 2, 4, 6, 8,10,12,14,16,18].digit(_Char)
[time3] int_const(_Char) * int_const("3") = [ 0, 3, 6, 9,12,15,18,21,24,27].digit(_Char)
[time4] int_const(_Char) * int_const("4") = [ 0, 4, 8,12,16,20,24,28,32,36].digit(_Char)
[time5] int_const(_Char) * int_const("5") = [ 0, 5,10,15,20,25,30,35,40,45].digit(_Char)
[time6] int_const(_Char) * int_const("6") = [ 0, 6,12,18,24,30,36,42,48,54].digit(_Char)
[time7] int_const(_Char) * int_const("7") = [ 0, 7,14,21,28,35,42,49,56,63].digit(_Char)
[time8] int_const(_Char) * int_const("8") = [ 0, 8,16,24,32,40,48,56,64,72].digit(_Char)
[time9] int_const(_Char) * int_const("9") = [ 0, 9,18,27,36,45,54,63,72,81].digit(_Char)

[time10] _Int * int_const("0") = 0
[time11] _Int * int_const(_Char) =
         _Int + _Int * ([0,0,1,2,3,4,5,6,7,8].digit(_Char))
         when int_const(_Char) != int_const("0")
[time12] int_const(_Char+1) * int_const(_Char+2 _Char) =
         int_const(_Char+ "0") + int_const(_Char+1) * int_const(_Char)
         when int_const(_Char+1) * int_const(_Char+2) = int_const(_Char+)

[time13]   _IntConst1 * - _IntConst2 = - (_IntConst1 * _IntConst2)
[time14] - _IntConst1 *   _IntConst2 = - (_IntConst1 * _IntConst2)
[time15] - _IntConst1 * - _IntConst2 =   _IntConst1 * _IntConst2

%% INT / INT -> INT (integer division)
[div1]   _IntConst1 / - _IntConst2 = - (_IntConst1 / _IntConst2)
[div2] - _IntConst1 /   _IntConst2 = - (_IntConst1 / _IntConst2)
[div3] - _IntConst1 / - _IntConst2 =   _IntConst1 / _IntConst2
[div4] _IntConst1 / _IntConst2 = 0
       when _IntConst2 > _IntConst1 = true
```

```
[div5] _IntConst1 / _IntConst2 =
       inc((_IntConst1 - _IntConst2) / _IntConst2)
       when _IntConst2 > _IntConst1 = false

%% INT $ INT -> INT (modulo)
[mod1]   _IntConst1 $ - _IntConst2 = - (_IntConst1 $ _IntConst2)
[mod2] - _IntConst1 $   _IntConst2 = - (_IntConst1 $ _IntConst2)
[mod3] - _IntConst1 $ - _IntConst2 =   _IntConst1 $ _IntConst2
[mod4] _IntConst1 $ _IntConst2 = _IntConst1
       when _IntConst2 > _IntConst1 = true
[mod5] _IntConst1 $ _IntConst2 =
       (_IntConst1 - _IntConst2) $ _IntConst2
       when _IntConst2 > _IntConst1 = false

%% INT = INT -> BOOL (equality)
[eq1] _IntConst1 = _IntConst2 ==>
      _IntConst1 =  _IntConst2 = true
[eq2] _IntConst1 != _IntConst2 ==>
      _IntConst1 =  _IntConst2 = false
[eq3]   _IntConst1 = - _IntConst2 = _IntConst1 = 0 & _IntConst2 = 0
[eq4] - _IntConst1 =   _IntConst2 = _IntConst1 = 0 & _IntConst2 = 0
[eq5] - _IntConst1 = - _IntConst2 = _IntConst1 = _IntConst2

%% INT <> INT -> BOOL (inequality)
[neq1] _Int1 <> _Int2 = !(_Int1 = _Int2)

%% INT > INT -> BOOL (greater than)
[gr0] int_const(_Char) > int_const("0") = [0,1,1,1,1,1,1,1,1,1].digit(_Char) = 1
[gr1] int_const(_Char) > int_const("1") = [0,0,1,1,1,1,1,1,1,1].digit(_Char) = 1
[gr2] int_const(_Char) > int_const("2") = [0,0,0,1,1,1,1,1,1,1].digit(_Char) = 1
[gr3] int_const(_Char) > int_const("3") = [0,0,0,0,1,1,1,1,1,1].digit(_Char) = 1
[gr4] int_const(_Char) > int_const("4") = [0,0,0,0,0,1,1,1,1,1].digit(_Char) = 1
[gr5] int_const(_Char) > int_const("5") = [0,0,0,0,0,0,1,1,1,1].digit(_Char) = 1
[gr6] int_const(_Char) > int_const("6") = [0,0,0,0,0,0,0,1,1,1].digit(_Char) = 1
[gr7] int_const(_Char) > int_const("7") = [0,0,0,0,0,0,0,0,1,1].digit(_Char) = 1
[gr8] int_const(_Char) > int_const("8") = [0,0,0,0,0,0,0,0,0,1].digit(_Char) = 1
[gr9] int_const(_Char) > int_const("9") = [0,0,0,0,0,0,0,0,0,0].digit(_Char) = 1

[gr10] int_const(_Char+1 _Char1) > int_const(_Char2) = true
[gr11] int_const(_Char1) > int_const(_Char+2 _Char2) = false
[gr12] int_const(_Char+1 _Char1) > int_const(_Char+2 _Char2) =
       (int_const(_Char+1) > int_const(_Char+2)) |
       ( (int_const(_Char+1) = int_const(_Char+2)) &
         (int_const(_Char1)  > int_const(_Char2) ) )
[gr13]   _IntConst1 > - _IntConst2 = !((_IntConst1 = 0) & (_IntConst1 = 0))
[gr14] - _IntConst1 >   _IntConst2 =  ((_IntConst1 = 0) & (_IntConst1 = 0))
[gr15] - _IntConst1 > - _IntConst2 = _IntConst2 > _IntConst1

%% INT < INT -> BOOL (smaller than)
[sm] _Int1 < _Int2 = _Int2 > _Int1

%% INT >= INT -> BOOL (greater equal)
[ge] _Int1 >= _Int2 = ((_Int1 > _Int2) | (_Int1 = _Int2))

%% INT <= INT -> BOOL (smaller equal)
[se] _Int1 <= _Int2 = ((_Int2 > _Int1) | (_Int2 = _Int1))

%% inc(INT) -> INT (increment)
  nc1] inc(int_const(_Char)) = [ 1, 2, 3, 4, 5, 6, 7, 8, 9,10].digit(_Char)
inc2] inc(int_const(_Char+ "9")) =
       int_const(_Char+1 "0")
       when inc(int_const(_Char+)) = int_const(_Char+1)
[inc3] inc(int_const(_Char+ _Char)) =
       int_const(_Char+ _Char1)
       when inc(int_const(_Char)) = int_const(_Char1)
[inc4] inc(- _Int) = - dec(_Int)

%% dec(INT) -> INT (decrement)
[dec1] dec(int_const(_Char)) = [-1, 0, 1, 2, 3, 4, 5, 6, 7, 8].digit(_Char)
[dec2] dec(int_const(_Char+ "0")) =
       int_const(_Char+1 "9")
       when dec(int_const(_Char+)) = int_const(_Char+1)
[dec3] dec(int_const(_Char+ _Char)) =
       int_const(_Char+ _Char1)
       when dec(int_const(_Char)) = int_const(_Char1)
[dec4] dec(- _Int) = - inc(_Int)

%% max(INT,INT) -> INT (maximum)
[max1] max(_Int1, _Int2) = _Int1
       when _Int1 >= _Int2 = true
[max2] max(_Int1, _Int2) = _Int2
       when _Int1 >= _Int2 = false

%% min(INT,INT) -> INT (minimum)
[min1] min(_Int1, _Int2) = _Int1
       when _Int1 >= _Int2 = false
[min2] min(_Int1, _Int2) = _Int2
       when _Int1 >= _Int2 = true

end Integers
```

```
module Reals

imports

  Layout
  Lisp
  Booleans
  Integers

exports

  sorts

    REAL_CONST
    REAL

  lexical syntax

    MANTISSA                    -> REAL_CONST
    MANTISSA EXPONENT           -> REAL_CONST

    [Ee] INT_CONST              -> EXPONENT
    [Ee] "+" INT_CONST          -> EXPONENT
    [Ee] "-" INT_CONST          -> EXPONENT

    INT_CONST "." INT_CONST     -> MANTISSA
    INT_CONST "."               -> MANTISSA
              "." INT_CONST     -> MANTISSA

  context-free syntax

    REAL_CONST                  -> REAL
    "+" REAL                    -> REAL
    "-" REAL                    -> REAL
    REAL "+" REAL               -> REAL {left}
    REAL "-" REAL               -> REAL {non-assoc}
    REAL "*" REAL               -> REAL {left}
    REAL "/" REAL               -> REAL {non-assoc}
    "(" REAL ")"                -> REAL {bracket}

    REAL "=" REAL               -> BOOL
    REAL "<>" REAL              -> BOOL
    REAL ">" REAL               -> BOOL
    REAL "<" REAL               -> BOOL
    REAL ">=" REAL              -> BOOL
    REAL "<=" REAL              -> BOOL

    max "(" REAL "," REAL ")"   -> REAL
    min "(" REAL "," REAL ")"   -> REAL

  variables

    "_RealConst"[0-9']*         -> REAL_CONST
    "_Real"[0-9']*              -> REAL

priorities

  { "+" REAL -> REAL, "-" REAL -> REAL} >
  { left: REAL "*" REAL -> REAL, REAL "/" REAL -> REAL} >
  { left: REAL "+" REAL -> REAL, REAL "-" REAL -> REAL}  >
  { REAL "=" REAL -> BOOL, REAL "<>" REAL -> BOOL,
    REAL ">" REAL -> BOOL, REAL ">=" REAL -> BOOL,
    REAL "<" REAL -> BOOL, REAL "<=" REAL -> BOOL }

hiddens

  sorts

    EXPONENT MANTISSA

  context-free syntax

    "LISP" LISP                 -> REAL
    "REAL" LISP                 -> REAL
    "<<" REAL ">>"              -> LISP
    "+"                         -> LISP
    "-"                         -> LISP
    "*"                         -> LISP
    "/"                         -> LISP
    "max"                       -> LISP
    "min"                       -> LISP

equations

[uplus] + _Real = _Real
[umin] -- _Real = _Real

[add1] _RealConst1 + _RealConst2 =
       REAL (convert-to-lexical << 1.0 >>
       (+ (convert-lexical-to-lisp << _RealConst1 >>)
```

```
          (convert-lexical-to-lisp << _RealConst2 >>)) )
[add2]    _RealConst1 + - _RealConst2 =   (_RealConst1 - _RealConst2)
[add3] - _RealConst1 +   _RealConst2 =   (_RealConst2 - _RealConst1)
[add4] - _RealConst1 + - _RealConst2 = - (_RealConst1 + _RealConst2)

[sub1] _RealConst1 - _RealConst2 =
       REAL (convert-to-lexical << 1.0 >>
       (- (convert-lexical-to-lisp << _RealConst1 >>)
          (convert-lexical-to-lisp << _RealConst2 >>)) )
[sub2]    _RealConst1 - - _RealConst2 =   (_RealConst1 + _RealConst2)
[sub3] - _RealConst1 -   _RealConst2 = - (_RealConst1 + _RealConst2)
[sub4] - _RealConst1 - - _RealConst2 =   (_RealConst2 - _RealConst1)

[mul1] _RealConst1 * _RealConst2 =
       REAL (convert-to-lexical << 1.0 >>
       (* (convert-lexical-to-lisp << _RealConst1 >>)
          (convert-lexical-to-lisp << _RealConst2 >>)) )
[mul2]    _RealConst1 * - _RealConst2 = - (_RealConst1 * _RealConst2)
[mul3] - _RealConst1 *   _RealConst2 = - (_RealConst1 * _RealConst2)
[mul4] - _RealConst1 * - _RealConst2 =   (_RealConst2 * _RealConst1)

[div1] _RealConst1 / _RealConst2 =
       REAL (convert-to-lexical << 1.0 >>
       (/ (convert-lexical-to-lisp << _RealConst1 >>)
          (convert-lexical-to-lisp << _RealConst2 >>)) )
[div2]    _RealConst1 / - _RealConst2 = - (_RealConst1 / _RealConst2)
[div3] - _RealConst1 /   _RealConst2 = - (_RealConst1 / _RealConst2)
[div4] - _RealConst1 / - _RealConst2 =   (_RealConst1 / _RealConst2)

[max1] max(_RealConst1, _RealConst2) =
       REAL (convert-to-lexical << 1.0 >>
            (max (convert-lexical-to-lisp << _RealConst1 >>)
                 (convert-lexical-to-lisp << _RealConst2 >>)) )

[min1] min(_RealConst1, _RealConst2) =
       REAL (convert-to-lexical << 1.0 >>
            (min (convert-lexical-to-lisp << _RealConst1 >>)
                 (convert-lexical-to-lisp << _RealConst2 >>)) )

[eq1] _RealConst1 = _RealConst2 = true
      when max(_RealConst1, _RealConst2) = min(_RealConst2, _RealConst1)
[eq2] _RealConst1 = _RealConst2 = false
      when max(_RealConst1, _RealConst2) != min(_RealConst2, _RealConst1)
[eq3]    _RealConst1 = - _RealConst2 = (_RealConst1 = 0.0) & (_RealConst2 = 0.0)
[eq4] - _RealConst1 =   _RealConst2 = (_RealConst1 = 0.0) & (_RealConst2 = 0.0)
[eq5] - _RealConst1 = - _RealConst2 = (_RealConst1 = _RealConst2)

[neq] _Real1 <> _Real2 = !(_Real1 = _Real2)

[gt1] _RealConst1 > _RealConst2 =
      (_RealConst1 = max(_RealConst1, _RealConst2)) &
      (_RealConst1 <> _RealConst2)
[gt2]    _RealConst1 > - _RealConst2 = !((_RealConst1 = 0.0) & (_RealConst2 = 0.0))
[gt3] - _RealConst1 >   _RealConst2 =  ((_RealConst1 = 0.0) & (_RealConst2 = 0.0))
[gt4] - _RealConst1 > - _RealConst2 = (_RealConst2 > _RealConst1)

[st]  _Real1 <  _Real2 = (_Real2 > _Real1)
[ge]  _Real1 >= _Real2 = (_Real1 > _Real2) | (_Real1 = _Real2)
 e]   _Real1 <= _Real2 = (_Real1 < _Real2) | (_Real1 = _Real2)

end Reals
```

```
module Chars

imports

  Layout
  Lisp
  Booleans
  Integers

exports

  sorts

    CHR

  lexical syntax

    ~[~] "~"                    -> CHR
    "~~"                        -> CHR

  context-free syntax

    CHR "=" CHR                 -> BOOL
    CHR "<>" CHR                -> BOOL
    CHR ">" CHR                 -> BOOL
    CHR "<" CHR                 -> BOOL
    CHR ">=" CHR                -> BOOL
    CHR "<=" CHR                -> BOOL

  variables

    "_Chr"[0-9']*               -> CHR

hiddens

  context-free syntax

    ord "(" CHR ")"             -> INT
    "INT" LISP                  -> INT
    "<<" INT ">>"               -> LISP
    "<<" CHR ">>"               -> LISP

equations

[ 1] ord(_Chr) =
     INT (convert-to-lexical
          << 1 >>
          (cascii (convert-lexical-to-lisp << _Chr >>)))

[ 2] _Chr = _Chr = true
[ 3] _Chr1 = _Chr2 = false
     when _Chr1 != _Chr2
[ 4] _Chr1 <> _Chr2 = !(_Chr1 = _Chr2)
[ 5] _Chr1 > _Chr2 = ord(_Chr1) > ord(_Chr2)
[ 6] _Chr1 < _Chr2 = ord(_Chr1) < ord(_Chr2)
[ 7] _Chr1 >= _Chr2 = ord(_Chr1) >= ord(_Chr2)
[ 8] _Chr1 <= _Chr2 = ord(_Chr1) <= ord(_Chr2)

end Chars
```

```
module Strings

imports

  Layout
  Booleans
  Integers
  Chars

exports

  sorts

    STR_CONST
    STR

  lexical syntax

    "'" ~[']* "'"                -> STR_CONST

  context-free syntax

    STR_CONST                    -> STR

    STR "+" STR                  -> STR { left }
    INT "*" STR                  -> STR

    STR "=" STR                  -> BOOL
    STR "<>" STR                 -> BOOL
    STR ">" STR                  -> BOOL
    STR "<" STR                  -> BOOL
    STR ">=" STR                 -> BOOL
    STR "<=" STR                 -> BOOL

    length "(" STR ")"           -> INT

  variables

    "_StrConst"[0-9]*            -> STR_CONST
    "_Str"[0-9]*                 -> STR

priorities

    STR "+" STR -> STR >
    { STR "=" STR -> BOOL, STR "<>" STR -> BOOL }

equations

[cat5]  str_const("'" _Char*1 "'") + str_const("'" _Char*2 "'") =
        str_const("'" _Char*1 _Char*2 "'")

[rep1] 0 * _Str = ''
[rep2] _Int > 0 = true ==>
       _Int * _Str = _Str + dec(_Int) * _Str

[eq1]  _StrConst1 = _StrConst2 ==>
       _StrConst1 = _StrConst2 = true
[eq2]  _StrConst1 != _StrConst2 ==>
       _StrConst1 = _StrConst2 = false

[neq1]  _StrConst1 <> _StrConst2 =
        !(_StrConst1 = _StrConst2)

[gr1] str_const("'" "'") > str_const("'" "'") = false
[gr2] str_const("'" _Char+ "'") > str_const("'" "'") = true
[gr3] str_const("'" "'") > str_const("'" _Char+ "'") = false
[gr4] str_const("'" _Char1 _Char*1 "'") > str_const("'" _Char2 _Char*2 "'") =
      chr(_Char1 "~") > chr(_Char2 "~")
      when chr(_Char1 "~") = chr(_Char2 "~") = false
[gr5] str_const("'" _Char1 _Char*1 "'") > str_const("'" _Char2 _Char*2 "'") =
      str_const("'" _Char*1 "'") > str_const("'" _Char*2 "'")
      when chr(_Char1 "~") = chr(_Char2 "~") = true

[sm1] _Str1 < _Str2 = _Str2 > _Str1
[ge1] _Str1 >= _Str2 = (_Str1 > _Str2) | (_Str1 = _Str2)
[se1] _Str1 <= _Str2 = (_Str2 > _Str1) | (_Str1 = _Str2)

[len0] length(str_const("'" "'")) = 0
[len1] length(str_const("'" _Char _Char* "'")) =
       inc(length(str_const("'" _Char* "'")))

end Strings
```

```
module Values

imports

  Layout
  Booleans
  Integers
  Reals
  Strings

exports

  sorts

    VAL

  lexical syntax

    "null"                          -> VAL

  context-free syntax

    BOOL                            -> VAL
    INT                             -> VAL
    REAL                            -> VAL
    STR                             -> VAL

    itor "(" INT ")"                -> REAL
    btos "(" BOOL ")"               -> STR
    itos "(" INT ")"                -> STR
    rtos "(" REAL ")"               -> STR

  variables

    "_Val"[0-9']*                   -> VAL
    "_Vals"[0-9']*                  -> {VAL ","}*

equations

[itor1] itor(int_const(_Char+)) = real_const(_Char+ ".")
[itor2] itor(- _Int) = - itor(_Int)

[btos1] btos(true) = 'true'
[btos2] btos(false) = 'false'

[itos1] itos(int_const(_Char+)) = str_const("'" _Char+ "'")
[itos2] itos(- _Int) = '-' + itos(_Int)

[rtos1] rtos(real_const(_Char+)) = str_const("'" _Char+ "'")
[rtos2] rtos(- _Real) = '-' + rtos(_Real)

end Values


module Variables

imports

  Layout

exports

  sorts

    VAR

  lexical syntax

    [A-Za-z][A-Za-z0-9_]*           -> VAR

  variables

    "_Var"[0-9']*                   -> VAR
    "_Vars"[0-9']*                  -> {VAR ","}*


end Variables
```

```
module Expressions

imports

  Layout
  Values
  Variables

exports

  sorts

    EXPR

  context-free syntax

    BOOL                        -> EXPR
    INT                         -> EXPR
    REAL                        -> EXPR
    STR                         -> EXPR
    VAR                         -> EXPR

    "!" EXPR                    -> EXPR
    "+" EXPR                    -> EXPR
    "-" EXPR                    -> EXPR

    EXPR "+" EXPR               -> EXPR { left }
    EXPR "-" EXPR               -> EXPR { left }
    EXPR "*" EXPR               -> EXPR { left }
    EXPR "/" EXPR               -> EXPR { left }

    EXPR "=" EXPR               -> EXPR { left }
    EXPR "<>" EXPR              -> EXPR { left }
    EXPR ">" EXPR               -> EXPR { left }
    EXPR "<" EXPR               -> EXPR { left }
    EXPR ">=" EXPR              -> EXPR { left }
    EXPR "<=" EXPR              -> EXPR { left }

    EXPR "&" EXPR               -> EXPR { left }
    EXPR "|" EXPR               -> EXPR { left }

    "(" EXPR ")"                -> EXPR { bracket }

    itor "(" EXPR ")"           -> EXPR
    btos "(" EXPR ")"           -> EXPR
    itos "(" EXPR ")"           -> EXPR
    rtos "(" EXPR ")"           -> EXPR

    bool "(" BOOL ")"           -> BOOL
    int "(" INT ")"             -> INT
    real "(" REAL ")"           -> REAL
    str "(" STR ")"             -> STR
    val "(" EXPR ")"            -> VAL

  variables

    "_Expr"[0-9']*              -> EXPR
    "_Exprs"[0-9']*             -> { EXPR "," }*

priorities

    { "!" EXPR -> EXPR, "+" EXPR -> EXPR, "-" EXPR -> EXPR } >
    { left: EXPR "*" EXPR -> EXPR, EXPR "/" EXPR -> EXPR } >
    { left: EXPR "+" EXPR -> EXPR, EXPR "-" EXPR -> EXPR } >
    { left: EXPR "=" EXPR -> EXPR, EXPR "<>" EXPR -> EXPR,
            EXPR ">" EXPR -> EXPR, EXPR ">=" EXPR -> EXPR,
            EXPR "<" EXPR -> EXPR, EXPR "<=" EXPR -> EXPR } >
    { left: EXPR "&" EXPR -> EXPR, EXPR "|" EXPR -> EXPR}

equations

[force1] bool(_Bool) = _Bool
[force2] int(_Int)   = _Int
[force3] real(_Real) = _Real
[force4] str(_Str)   = _Str

[val1] val(_Bool) = _Bool
[val2] val(_Int)  = _Int
[val3] val(_Real) = _Real
[val4] val(_Str)  = _Str

[not1] ! _Expr = bool(! _Bool) when _Expr = _Bool
[not2] ! _Expr = null when _Expr = _Int
[not3] ! _Expr = null when _Expr = _Real
[not4] ! _Expr = null when _Expr = _Str
[not5] ! _Expr = null when _Expr = null

[plus1] + _Expr = int(_Int) when _Expr = _Int
[plus2] + _Expr = real(_Real) when _Expr = _Real
```

```
[umin1] - _Expr = int(- _Int) when _Expr = _Int
[umin2] - _Expr = real(- _Real) when _Expr = _Real

[add1]  _Expr1 + _Expr2 = int(_Int1 + _Int2)
        when _Expr1 = _Int1, _Expr2 = _Int2
[add2]  _Expr1 + _Expr2 = real(_Real1 + _Real2)
        when _Expr1 = _Real1, _Expr2 = _Real2
[add3]  _Expr1 + _Expr2 = real(_Real + itor(_Int))
        when _Expr1 = _Real, _Expr2 = _Int
[add4]  _Expr1 + _Expr2 = real(itor(_Int) + _Real)
        when _Expr1 = _Int, _Expr2 = _Real
[add5]  _Expr1 + _Expr2 = str(_Str1 + _Str2)
        when _Expr1 = _Str1, _Expr2 = _Str2
%%[add*] default: _Expr1 + _Expr2 = null
[add6]  _Expr1 + _Expr2 = null when _Expr1 = _Bool1, _Expr2 = _Bool2
[add7]  _Expr1 + _Expr2 = null when _Expr1 = _Bool,  _Expr2 = _Int
[add8]  _Expr1 + _Expr2 = null when _Expr1 = _Bool,  _Expr2 = _Real
[add9]  _Expr1 + _Expr2 = null when _Expr1 = _Bool,  _Expr2 = _Str
[add10] _Expr1 + _Expr2 = null when _Expr1 = _Bool,  _Expr2 = null
[add11] _Expr1 + _Expr2 = null when _Expr1 = _Int,   _Expr2 = _Bool
[add12] _Expr1 + _Expr2 = null when _Expr1 = _Int,   _Expr2 = _Str
[add13] _Expr1 + _Expr2 = null when _Expr1 = _Int,   _Expr2 = null
[add14] _Expr1 + _Expr2 = null when _Expr1 = _Real,  _Expr2 = _Bool
[add15] _Expr1 + _Expr2 = null when _Expr1 = _Real,  _Expr2 = _Str
[add16] _Expr1 + _Expr2 = null when _Expr1 = _Real,  _Expr2 = null
[add17] _Expr1 + _Expr2 = null when _Expr1 = _Str,   _Expr2 = _Bool
[add18] _Expr1 + _Expr2 = null when _Expr1 = _Str,   _Expr2 = _Int
[add19] _Expr1 + _Expr2 = null when _Expr1 = _Str,   _Expr2 = _Real
[add20] _Expr1 + _Expr2 = null when _Expr1 = _Str,   _Expr2 = null
[add21] _Expr1 + _Expr2 = null when _Expr1 = null,  _Expr2 = _Bool
[add22] _Expr1 + _Expr2 = null when _Expr1 = null,  _Expr2 = _Int
[add23] _Expr1 + _Expr2 = null when _Expr1 = null,  _Expr2 = _Real
[add24] _Expr1 + _Expr2 = null when _Expr1 = null,  _Expr2 = _Str
[add25] _Expr1 + _Expr2 = null when _Expr1 = null,  _Expr2 = null

[sub1] _Expr1 - _Expr2 = int(_Int1 - _Int2)
       when _Expr1 = _Int1, _Expr2 = _Int2
[sub2] _Expr1 - _Expr2 = real(_Real1 - _Real2)
       when _Expr1 = _Real1, _Expr2 = _Real2
[sub3] _Expr1 - _Expr2 = real(itor(_Int) - _Real)
       when _Expr1 = _Int, _Expr2 = _Real
[sub4] _Expr1 - _Expr2 = real(_Real - itor(_Int))
       when _Expr1 = _Real, _Expr2 = _Int

[mul1] _Expr1 * _Expr2 = int(_Int1 * _Int2)
       when _Expr1 = _Int1, _Expr2 = _Int2
[mul2] _Expr1 * _Expr2 = real(_Real1 * _Real2)
       when _Expr1 = _Real1, _Expr2 = _Real2
[mul3] _Expr1 * _Expr2 = real(itor(_Int) * _Real)
       when _Expr1 = _Int, _Expr2 = _Real
[mul4] _Expr1 * _Expr2 = real(_Real * itor(_Int))
       when _Expr1 = _Real, _Expr2 = _Int
[mul5] _Expr1 * _Expr2 = str(_Int * _Str)
       when _Expr1 = _Int, _Expr2 = _Str

[div1] _Expr1 / _Expr2 = int(_Int1 / _Int2)
       when _Expr1 = _Int1, _Expr2 = _Int2
[div2] _Expr1 / _Expr2 = real(_Real1 / _Real2)
       when _Expr1 = _Real1, _Expr2 = _Real2
[div3] _Expr1 / _Expr2 = real(itor(_Int) / _Real)
       when _Expr1 = _Int, _Expr2 = _Real
[div4] _Expr1 / _Expr2 = real(_Real / itor(_Int))
       when _Expr1 = _Real, _Expr2 = _Int

[eq11] (_Expr1 = _Expr2) = bool(_Bool1 = _Bool2)    when _Expr1 = _Bool1, _Expr2 = _Bool2
[eq12] (_Expr1 = _Expr2) = null                     when _Expr1 = _Bool,  _Expr2 = _Int
[eq13] (_Expr1 = _Expr2) = null                     when _Expr1 = _Bool,  _Expr2 = _Real
[eq14] (_Expr1 = _Expr2) = null                     when _Expr1 = _Bool,  _Expr2 = _Str
[eq21] (_Expr1 = _Expr2) = null                     when _Expr1 = _Int,   _Expr2 = _Bool
[eq22] (_Expr1 = _Expr2) = bool(_Int1 = _Int2)      when _Expr1 = _Int1,  _Expr2 = _Int2
[eq23] (_Expr1 = _Expr2) = bool(itor(_Int) = _Real) when _Expr1 = _Int,   _Expr2 = _Real
[eq24] (_Expr1 = _Expr2) = null                     when _Expr1 = _Int,   _Expr2 = _Str
[eq31] (_Expr1 = _Expr2) = null                     when _Expr1 = _Real,  _Expr2 = _Bool
[eq32] (_Expr1 = _Expr2) = bool(_Real = itor(_Int)) when _Expr1 = _Real,  _Expr2 = _Int
[eq33] (_Expr1 = _Expr2) = bool(_Real1 = _Real2)    when _Expr1 = _Real1, _Expr2 = _Real2
[eq34] (_Expr1 = _Expr2) = null                     when _Expr1 = _Real,  _Expr2 = _Str
[eq41] (_Expr1 = _Expr2) = null                     when _Expr1 = _Str,   _Expr2 = _Bool
[eq42] (_Expr1 = _Expr2) = null                     when _Expr1 = _Str,   _Expr2 = _Int
[eq43] (_Expr1 = _Expr2) = null                     when _Expr1 = _Str,   _Expr2 = _Real
[eq44] (_Expr1 = _Expr2) = bool(_Str1 = _Str2)      when _Expr1 = _Str1,  _Expr2 = _Str2
[eq51] (_Expr = null) = null
[eq52] (null = _Expr) = null

[neq1] _Expr1 <> _Expr2 = !(_Expr1 = _Expr2)

[gt1] (_Expr1 > _Expr2) = bool(_Int1 > _Int2)
      when _Expr1 = _Int1, _Expr2 = _Int2
[gt2] (_Expr1 > _Expr2) = bool(_Real1 > _Real2)
      when _Expr1 = _Real1, _Expr2 = _Real2
[gt3] (_Expr1 > _Expr2) = bool(itor(_Int) > _Real)
```

```
      when _Expr1 = _Int, _Expr2 = _Real
[gt4] (_Expr1 > _Expr2) = bool(_Real > itor(_Int))
      when _Expr1 = _Real, _Expr2 = _Int
[gt5] (_Expr1 > _Expr2) = bool(_Str1 > _Str2)
      when _Expr1 = _Str1, _Expr2 = _Str2
[gt6] (_Expr > null) = null
[gt7] (null > _Expr) = null

[st1] _Expr1 < _Expr2 = (_Expr2 > _Expr1)

[ge1] _Expr1 >= _Expr2 = (_Expr1 > _Expr2) | (_Expr1 = _Expr2)

[se1] _Expr1 <= _Expr2 = (_Expr1 < _Expr2) | (_Expr1 = _Expr2)

[and1] _Expr1 & _Expr2 = bool(_Bool1 & _Bool2)
       when _Expr1 = _Bool1, _Expr2 = _Bool2
[and2] _Expr & null = bool(false) when _Expr  = bool(false)
[and3] _Expr & null = null        when _Expr != bool(false)
[and4] null & _Expr = bool(false) when _Expr  = bool(false)
[and5] null & _Expr = null        when _Expr != bool(false)
[and6] null & null = null

[or1] _Expr1 | _Expr2 = bool(_Bool1 | _Bool2)
      when _Expr1 = _Bool1, _Expr2 = _Bool2
[or2] _Expr | null = bool(true) when _Expr  = bool(true)
[or3] _Expr | null = null       when _Expr != bool(true)
[or4] null | _Expr = bool(true) when _Expr  = bool(true)
[or5] null | _Expr = null       when _Expr != bool(true)
[or6] null | null = null

[itor1] itor(_Expr) = real(itor(_Int)) when
        _Expr = _Int

[btos1] btos(_Expr) = str(btos(_Bool)) when
        _Expr = _Bool

[itos1] itos(_Expr) = str(itos(_Int)) when
        _Expr = _Int

[rtos1] rtos(_Expr) = str(rtos(_Real)) when
        _Expr = _Real

end Expressions
```

```
module Tuples

imports

  Layout
  Values
  Expressions

exports

  sorts

    VAL_TUP
    VAR_TUP
    EXPR_TUP
    INST
    INST_TUP

  context-free syntax

    "<" { VAL "," }* ">"                -> VAL_TUP
    "<" { VAR  ","}* ">"                -> VAR_TUP
    "<" { EXPR "," }* ">"               -> EXPR_TUP
    VAR ":" VAL                         -> INST
    "<" { INST ","}* ">"                -> INST_TUP

    VAL_TUP "=" VAL_TUP                 -> BOOL

    inst "(" VAR_TUP "," VAL_TUP ")"    -> INST_TUP
    bind "(" INST_TUP "," EXPR ")"      -> EXPR
    bind "(" INST_TUP "," EXPR_TUP ")"  -> EXPR_TUP
    val "(" EXPR_TUP ")"                -> VAL_TUP


  variables

    "_ValTup"[0-9']*                    -> VAL_TUP
    "_ValTup*"[0-9']*                   -> {VAL_TUP ","}*
    "_VarTup"[0-9']*                    -> VAR_TUP
    "_ExprTup"[0-9']*                   -> EXPR_TUP
    "_Inst"[0-9']*                      -> INST
    "_Insts"[0-9']*                     -> {INST ","}*
    "_InstTup"[0-9']*                   -> INST_TUP

hiddens

  context-free syntax

    eq "(" VAL_TUP "," VAL_TUP ")"      -> BOOL

equations

[eq1 ] (_ValTup1 = _ValTup2) = true
       when eq(_ValTup1, _ValTup2) = true
[eq2 ] (_ValTup1 = _ValTup2) = false
       when eq(_ValTup1, _ValTup2) != true

[eq3 ] eq(< >, < >) = true
[eq4 ] eq(<_Val>, < >) = false
[eq5 ] eq(< >, <_Val>) = false
[eq6 ] eq(<_Bool1, _Vals1>, <_Bool2, _Vals2>) =
       (_Bool1 = _Bool2) & eq(<_Vals1>, <_Vals2>)
[eq7 ] eq(<_Int1, _Vals1>, <_Int2, _Vals2>) =
       (_Int1 = _Int2) & eq(<_Vals1>, <_Vals2>)
[eq8 ] eq(<_Real1, _Vals1>, <_Real2, _Vals2>) =
       (_Real1 = _Real2) & eq(<_Vals1>, <_Vals2>)
[eq9 ] eq(<_Str1, _Vals1>, <_Str2, _Vals2>) =
       (_Str1 = _Str2) & eq(<_Vals1>, <_Vals2>)
[eq10] eq(<null, _Vals1>, <null, _Vals2>) =
       eq(<_Vals1>, <_Vals2>)

[inst1] inst(< >,< >) = < >
[inst2] inst(<_Var, _Vars>, <_Val, _Vals>) = <_Var : _Val, _Insts>
        when inst(<_Vars>, <_Vals>) = <_Insts>

[val1] val(< >) = < >
[val2] val(<_Expr, _Exprs>) = <_Val, _Vals>
       when val(_Expr) = _Val, val(<_Exprs>) = <_Vals>

[bind0] bind(< >, _Var) = _Var
[bind1] bind(<_Var : _Bool, _Insts>, _Var) = _Bool
[bind2] bind(<_Var : _Int,  _Insts>, _Var) = _Int
[bind3] bind(<_Var : _Real, _Insts>, _Var) = _Real
[bind4] bind(<_Var : _Str,  _Insts>, _Var) = _Str
[bind5] bind(<_Var : null,  _Insts>, _Var) = null
[bind6] bind(<_Var : _Val,  _Insts>, _Var') =
        bind(<_Insts>, _Var')
        when _Var != _Var'

[const1] bind(_InstTup, _Bool) = _Bool
```

```
[const2] bind(_InstTup, _Int)  = _Int
[const3] bind(_InstTup, _Real)  = _Real
[const4] bind(_InstTup, _Str)  = _Str
[const5] bind(_InstTup, null)  = null

[not1] bind(_InstTup, ! _Expr) = ! bind(_InstTup, _Expr)

[plus1] bind(_InstTup, + _Expr) = + bind(_InstTup, _Expr)

[min1] bind(_InstTup, - _Expr) = - bind(_InstTup, _Expr)

[add1] bind(_InstTup, _Expr1 + _Expr2) =
       bind(_InstTup, _Expr1) + bind(_InstTup, _Expr2)

[sub1] bind(_InstTup, _Expr1 - _Expr2) =
       bind(_InstTup, _Expr1) - bind(_InstTup, _Expr2)

[mul1] bind(_InstTup, _Expr1 * _Expr2) =
       bind(_InstTup, _Expr1) * bind(_InstTup, _Expr2)

[div1] bind(_InstTup, _Expr1 / _Expr2) =
       bind(_InstTup, _Expr1) / bind(_InstTup, _Expr2)

[eq1] bind(_InstTup, _Expr1 = _Expr2) =
      (bind(_InstTup, _Expr1) = bind(_InstTup, _Expr2))

[neq1] bind(_InstTup, _Expr1 <> _Expr2) =
       bind(_InstTup, _Expr1) <> bind(_InstTup, _Expr2)

[gt1] bind(_InstTup, _Expr1 > _Expr2) =
      bind(_InstTup, _Expr1) > bind(_InstTup, _Expr2)

[st] bind(_InstTup, _Expr1 < _Expr2) =
     bind(_InstTup, _Expr1) < bind(_InstTup, _Expr2)

[ge1] bind(_InstTup, _Expr1 >= _Expr2) =
      bind(_InstTup, _Expr1) >= bind(_InstTup, _Expr2)

[se1] bind(_InstTup, _Expr1 <= _Expr2) =
      bind(_InstTup, _Expr1) <= bind(_InstTup, _Expr2)

[and1] bind(_InstTup, _Expr1 & _Expr2) =
       bind(_InstTup, _Expr1) & bind(_InstTup, _Expr2)

[or1] bind(_InstTup, _Expr1 | _Expr2) =
      bind(_InstTup, _Expr1) | bind(_InstTup, _Expr2)

[itor1] bind(_InstTup, itor(_Expr)) =
     itor(bind(_InstTup, _Expr))

[btos1] bind(_InstTup, btos(_Expr)) =
        btos(bind(_InstTup, _Expr))

[itos1] bind(_InstTup, itos(_Expr)) =
        itos(bind(_InstTup, _Expr))

[rtos1] bind(_InstTup, rtos(_Expr)) =
        rtos(bind(_InstTup, _Expr))

[tup1] bind(_InstTup, < >) = < >
[tup2] bind(_InstTup, <_Expr, _Exprs>) =
       <bind(_InstTup, _Expr), _Exprs'>
       when bind(_InstTup, <_Exprs>) = <_Exprs'>

end Tuples
```

```
module Relations

imports

  Layout
  Booleans
  Values
  Expressions
  Tuples

exports

  sorts

    REL

  context-free syntax

    VAR                                  -> REL
    "{" {VAL_TUP ","}* "}"               -> REL
    "!" REL                              -> REL
    REL "+" REL                          -> REL  { left }
    REL "-" REL                          -> REL  { left }
    REL "*" REL                          -> REL  { left }
    REL "#" REL                          -> REL  { left }
    "(" REL ")"                          -> REL  { bracket }

    VAL_TUP "@" REL                      -> BOOL
    "#" REL                              -> INT

    for_all  VAR_TUP "@" REL ":" EXPR    -> BOOL
    there_is VAR_TUP "@" REL ":" EXPR    -> BOOL

    sum "(" REL ")"                      -> EXPR
    inf "(" REL ")"                      -> EXPR
    sup "(" REL ")"                      -> EXPR

    EXPR_TUP "@" REL                     -> EXPR

    "{" EXPR_TUP "<-" VAR_TUP "@" REL "|" EXPR "}"      -> REL
    "{" EXPR_TUP "<-" VAR_TUP "@" REL "}"               -> REL
    "{" VAR_TUP "@" REL "|" EXPR "}"                    -> REL
    "{" VAR_TUP "@" REL "}"                             -> REL

  variables

    "_Rel"[0-9]*                         -> REL

hiddens

  context-free syntax

    rbind "(" INST_TUP "," REL ")"                      -> REL
    scope-cover "(" INST_TUP "," VAR_TUP ")"            -> INST_TUP
    doesnt-occur "(" VAR "," VAR_TUP ")"                -> BOOL

  variables

    "_vt"[0-9']*                 -> VAL_TUP
    "_vt*"[0-9']*                -> {VAL_TUP ","}*
    "_vt+"[0-9']*                -> {VAL_TUP ","}+

%%priorities: # > + ??

equations

%% [norm] {_vt*1, _vt, _vt*2, _vt, _vt*3} = {_vt*1, _vt, _vt*2, _vt*3}

[unique1] !{ } = { }
[unique2] !{_vt, _vt*} = {_vt} + !({_vt*} - {_vt})

[union] {_vt*1} + {_vt*2} = {_vt*1, _vt*2}

[diff1] { } - {_vt*} = {}
[diff2] {_vt, _vt*1} - {_vt*2} = {_vt} + ({_vt*1} - {_vt*2})
        when _vt @ {_vt*2} != true
[diff3] {_vt, _vt*1} - {_vt*2} =          {_vt*1} - {_vt*2}
        when _vt @ {_vt*2} = true

[intrs1] { } * {_vt*} = { }
[intrs2] {_vt, _vt*1} * {_vt*2} = {_vt} + ({_vt*1} * {_vt*2})
         when _vt @ {_vt*2} = true
[intrs3] {_vt, _vt*1} * {_vt*2} =          {_vt*1} * {_vt*2}
         when _vt @ {_vt*2} != true

%% cave order of elements: {a,b} # {x, y} = {ax, ay, bx, by}

[prod1] { } # {_vt*} = { }
[prod2] {_vt*} # { } = { }
[prod3] {<_Vals1>, _vt*1} # {<_Vals2>, _vt*2} =
```

```
        {<_Vals1, _Vals2>} +
        ({<_Vals1>} # {_vt*2}) +
        ({_vt*1} # {<_Vals2>, _vt*2})

[elem1] _vt1 @ { } = false
[elem2] _vt1 @ {_vt2, _vt*2} = true
        when (_vt1 = _vt2) = true
[elem3] _vt1 @ {_vt2, _vt*2} = _vt1 @ {_vt*2}
        when (_vt1 = _vt2) = false

[count1] # { } = 0
[count2] # {_vt, _vt*} = 1 + # {_vt*}

[select0] {_VarTup @ _Rel} = _Rel
[select1] {_VarTup @ { } | _Expr} = { }
[select2] {_VarTup @ {_ValTup, _ValTup*} | _Expr} =
          {_VarTup @ {_ValTup*} | _Expr}
          when bind(inst(_VarTup, _ValTup), _Expr) != bool(true)
[select3] {_VarTup @ {_ValTup, _ValTup*} | _Expr} =
          {_ValTup} + {_VarTup @ {_ValTup*} | _Expr}
          when bind(inst(_VarTup, _ValTup), _Expr) = bool(true)

[query0] {_ExprTup <- _VarTup @ { } } = { }
[query1] {_ExprTup <- _VarTup @ {_ValTup, _ValTup*}} =
         {val(bind(inst(_VarTup, _ValTup), _ExprTup))} +
         {_ExprTup <- _VarTup @ {_ValTup*}}
[query2] {_ExprTup <- _VarTup @ { } | _Expr} = { }
[query3] {_ExprTup <- _VarTup @ {_ValTup, _ValTup*} | _Expr} =
         {_ExprTup <- _VarTup @ {_ValTup*} | _Expr}
         when bind(inst(_VarTup, _ValTup), _Expr) != bool(true)
[query4] {_ExprTup <- _VarTup @ {_ValTup, _ValTup*} | _Expr} =
         {val(bind(_InstTup, _ExprTup))} +
         {_ExprTup <- _VarTup @ {_ValTup*} | _Expr}
         when inst(_VarTup, _ValTup) = _InstTup,
              bind(_InstTup, _Expr) = bool(true)

[subq] bind(_InstTup, _ExprTup @ _Rel) =
       val(bind(_InstTup, _ExprTup)) @ rbind(_InstTup, _Rel)

[all ] bind(_InstTup, for_all _VarTup @ _Rel : _Expr) =
       for_all _VarTup @ rbind(_InstTup', _Rel) : bind(_InstTup', _Expr)
       when scope-cover(_InstTup, _VarTup) = _InstTup'
[any ] bind(_InstTup, there_is _VarTup @ _Rel : _Expr) =
       there_is _VarTup @ rbind(_InstTup', _Rel) : bind(_InstTup', _Expr)
       when scope-cover(_InstTup, _VarTup) = _InstTup'

[rbind1] rbind(_InstTup, _Var) = _Var
[rbind2] rbind(_InstTup, {_vt*}) = {_vt*}
[rbind3] rbind(_InstTup, ! _Rel) = ! rbind(_InstTup, _Rel)
[rbind4] rbind(_InstTup, _Rel1 + _Rel2) =
         rbind(_InstTup, _Rel1) + rbind(_InstTup, _Rel2)
[rbind5] rbind(_InstTup, _Rel1 - _Rel2) =
         rbind(_InstTup, _Rel1) - rbind(_InstTup, _Rel2)
[rbind6] rbind(_InstTup, _Rel1 * _Rel2) =
         rbind(_InstTup, _Rel1) * rbind(_InstTup, _Rel2)
[rbind7] rbind(_InstTup, _Rel1 # _Rel2) =
         rbind(_InstTup, _Rel1) # rbind(_InstTup, _Rel2)
[rbind8] rbind(_InstTup, {_ExprTup <- _VarTup @ _Rel | _Expr }) =
         { bind(_InstTup', _ExprTup) <-
         _VarTup @ rbind(_InstTup', _Rel) |
         bind(_InstTup', _Expr) }
         when _InstTup' = scope-cover(_InstTup, _VarTup)
[rbind9] rbind(_InstTup, {_ExprTup <- _VarTup @ _Rel }) =
         { bind(_InstTup', _ExprTup) <-
         _VarTup @ rbind(_InstTup', _Rel) }
         when _InstTup' = scope-cover(_InstTup, _VarTup)
[rbind10] rbind(_InstTup, {_VarTup @ _Rel | _Expr }) =
          { _VarTup @ rbind(_InstTup', _Rel) |
          bind(_InstTup', _Expr) }
          when _InstTup' = scope-cover(_InstTup, _VarTup)
[rbind11] rbind(_InstTup, {_VarTup @ _Rel }) =
          { _VarTup @ rbind(_InstTup', _Rel) }
          when _InstTup' = scope-cover(_InstTup, _VarTup)

[cover1] scope-cover(<>, _VarTup) = <>
[cover2] scope-cover(<_Var : _Val, _Insts>, _VarTup) =
         <_Var : _Val, _Insts'>
         when doesnt-occur(_Var, _VarTup) = true,
              scope-cover(<_Insts>, _VarTup) = <_Insts'>
[cover3] scope-cover(<_Var : _Val, _Insts>, _VarTup) =
         <_Insts'>
         when doesnt-occur(_Var, _VarTup) = false,
              scope-cover(<_Insts>, _VarTup) = <_Insts'>

[occur1] doesnt-occur(_Var, <>) = true
[occur2] doesnt-occur(_Var, <_Var, _Vars>) = false
[occur3] doesnt-occur(_Var, <_Var', _Vars>) =
         doesnt-occur(_Var, <_Vars>)
         when _Var != _Var'
```

```
[A1] for_all _VarTup @ { } : _Expr = bool(true)
[A2] for_all _VarTup @ {_ValTup, _ValTup*} : _Expr =
     for_all _VarTup @ {_ValTup*} : _Expr
     when bind(inst(_VarTup, _ValTup), _Expr) = bool(true)
[A2] for_all _VarTup @ {_ValTup, _ValTup*} : _Expr = false
     when bind(inst(_VarTup, _ValTup), _Expr) = bool(false)

[E1] there_is _VarTup @ { } : _Expr = bool(false)
[E2] there_is _VarTup @ {_ValTup, _ValTup*} : _Expr = bool(true)
     when bind(inst(_VarTup, _ValTup), _Expr) = bool(true)
[E3] there_is _VarTup @ {_ValTup, _ValTup*} : _Expr =
     there_is _VarTup @ {_ValTup*} : _Expr
     when bind(inst(_VarTup, _ValTup), _Expr) = bool(false)

[sum1] sum({ }) = null
[sum2] sum({<_Int>})  = _Int
[sum3] sum({<_Real>}) = _Real
[sum4] sum({<_Str>})  = _Str
[sum5] sum({<_Int1>,  <_Int2>,  _vt*}) = _Int1  + sum({<_Int2>,  _vt*})
[sum6] sum({<_Real1>, <_Real2>, _vt*}) = _Real1 + sum({<_Real2>, _vt*})
[sum7] sum({<_Str1>,  <_Str2>,  _vt*}) = _Str1  + sum({<_Str2>,  _vt*})

[inf0] inf({}) = null
[inf1] inf({<_Int>})  = _Int
[inf2] inf({<_Real>}) = _Real
[inf3] inf({<_Str>})  = _Str
[inf4] inf({<_Int1>, <_Int2>, _vt*}) =
       inf({<min(_Int1, _Int2)>, _vt*})
[inf5] inf({<_Real1>, <_Real2>, _vt*}) =
       inf({<min(_Real1, _Real2)>, _vt*})
[inf6] inf({<_Str1>, <_Str2>, _vt*}) =
       inf({<_Str1>, _vt*}) when _Str2 > _Str1 = true
[inf7] inf({<_Str1>, <_Str2>, _vt*}) =
       inf({<_Str2>, _vt*}) when _Str1 > _Str2 = true

[sup0] sup({}) = null
[sup1] sup({<_Int>})  = _Int
[sup2] sup({<_Real>}) = _Real
[sup3] sup({<_Str>})  = _Str
[sup4] sup({<_Int1>, <_Int2>, _vt*}) =
       sup({<max(_Int1, _Int2)>, _vt*})
[sup5] sup({<_Real1>, <_Real2>, _vt*}) =
       sup({<max(_Real1, _Real2)>, _vt*})
[sup6] sup({<_Str1>, <_Str2>, _vt*}) =
       sup({<_Str1>, _vt*}) when _Str1 > _Str2 = true
[sup7] sup({<_Str1>, <_Str2>, _vt*}) =
       sup({<_Str2>, _vt*}) when _Str2 > _Str1 = true

end Relations
```

```
module RDBS

imports

  Relations

exports

  sorts

    EXE
    ENV
    PROG
    SCHEMA
    DBASE
    RDEF
    RINST
    STAT

  context-free syntax

    ENV PROG                        -> EXE

    SCHEMA DBASE                    -> ENV
    "schema" RDEF*                  -> SCHEMA
    "database" RINST*               -> DBASE

    VAR "==" REL                    -> RDEF
    VAR "<=" REL                    -> RDEF
    VAR "=" REL                     -> RINST

    "program" STAT* "end"           -> PROG
    VAR "<-" REL ";"                -> STAT

    "{" EXPR_TUP "<-" "@" REL "|" EXPR "}"      -> REL
    "{"               "@" REL "|" EXPR "}"      -> REL

    exec "(" SCHEMA "," DBASE "," REL ")"       -> REL

  variables

    "_Env"[0-9']*                   -> ENV
    "_Schema"[0-9']*                -> SCHEMA
    "_Dbase"[0-9']*                 -> DBASE
    "_RDef"[0-9']*                  -> RDEF
    "_RDef*"[0-9']*                 -> RDEF*
    "_RInst*"[0-9']*                -> RINST*
    "_Stat"[0-9']*                  -> STAT
    "_Stat*"[0-9']*                 -> STAT*

hiddens

  context-free syntax

    pexec "(" ENV "," STAT ")"                  -> ENV
    assign "(" DBASE "," RINST ")"              -> DBASE
    erel "(" SCHEMA "," DBASE "," REL ")"       -> REL
    eval "(" SCHEMA "," DBASE "," EXPR ")"      -> EXPR
    lookup "(" DBASE "," VAR ")"                -> REL
    attrs "(" SCHEMA "," REL ")"                -> VAR_TUP
    attrs "(" RDEF "," VAR ")"                  -> VAR_TUP

equations

[ 0] exec(_Schema, _Dbase, _Rel) =
     erel(_Schema, _Dbase, _Rel)

[ 1] _Env program _Stat _Stat* end =
     pexec(_Env, _Stat) program _Stat* end

[ 2] pexec(_Schema _Dbase, _Var <- _Rel;) =
     _Schema assign(_Dbase, _Var = erel(_Schema, _Dbase, _Rel))

[ 3] assign(database _RInst*1 _Var = _Rel1 _RInst*2, _Var = _Rel2) =
     database _RInst*1 _Var = _Rel2 _RInst*2

[ 4] erel(_Schema, _Dbase, { _ValTup* }) =
     { _ValTup* }
[ 5] erel(_Schema, _Dbase, ! _Rel) =
     ! erel(_Schema, _Dbase, _Rel)
[ 6] erel(_Schema, _Dbase, _Rel1 + _Rel2) =
     erel(_Schema, _Dbase, _Rel1) + erel(_Schema, _Dbase, _Rel2)
[ 7] erel(_Schema, _Dbase, _Rel1 - _Rel2) =
     erel(_Schema, _Dbase, _Rel1) - erel(_Schema, _Dbase, _Rel2)
[ 8] erel(_Schema, _Dbase, _Rel1 * _Rel2) =
     erel(_Schema, _Dbase, _Rel1) * erel(_Schema, _Dbase, _Rel2)
[ 9] erel(_Schema, _Dbase, _Rel1 # _Rel2) =
     erel(_Schema, _Dbase, _Rel1) # erel(_Schema, _Dbase, _Rel2)
[10] erel(_Schema, _Dbase, { _ExprTup <- _VarTup @ _Rel | _Expr }) =
     { _ExprTup <- _VarTup @ erel(_Schema, _Dbase, _Rel) |
```

```
        eval(_Schema, _Dbase, _Expr) }
 [11] erel(_Schema, _Dbase, {_VarTup @ _Rel | _Expr}) =
      { _VarTup @ erel(_Schema, _Dbase, _Rel) | eval(_Schema, _Dbase, _Expr) }
 [12] erel(_Schema, _Dbase, _Var) =
      erel(_Schema, _Dbase, lookup(_Dbase, _Var))

 [13] lookup(database, _Var) = _Var
 [14] lookup(database _Var = _Rel _RInst*, _Var) = _Rel
 [15] lookup(database _Var = _Rel _RInst*, _Var1) =
      lookup(database _RInst*, _Var1)
      when _Var1 != _Var

 [16] eval(_Schema, _Dbase, _Var) = _Var
 [17] eval(_Schema, _Dbase, _BoolConst) = _BoolConst
 [18] eval(_Schema, _Dbase, _IntConst) = _IntConst
 [19] eval(_Schema, _Dbase, _RealConst) = _RealConst
 [20] eval(_Schema, _Dbase, _StrConst) = _StrConst
 [21] eval(_Schema, _Dbase, _Expr1 + _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) + eval(_Schema, _Dbase, _Expr2))
 [22] eval(_Schema, _Dbase, _Expr1 - _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) - eval(_Schema, _Dbase, _Expr2))
 [23] eval(_Schema, _Dbase, _Expr1 * _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) * eval(_Schema, _Dbase, _Expr2))
 [24] eval(_Schema, _Dbase, _Expr1 / _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) / eval(_Schema, _Dbase, _Expr2))
 [25] eval(_Schema, _Dbase, _Expr1 = _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) = eval(_Schema, _Dbase, _Expr2))
 [26] eval(_Schema, _Dbase, _Expr1 <> _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) <> eval(_Schema, _Dbase, _Expr2))
 [27] eval(_Schema, _Dbase, _Expr1 > _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) > eval(_Schema, _Dbase, _Expr2))
 [28] eval(_Schema, _Dbase, _Expr1 < _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) < eval(_Schema, _Dbase, _Expr2))
 [29] eval(_Schema, _Dbase, _Expr1 >= _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) >= eval(_Schema, _Dbase, _Expr2))
 [30] eval(_Schema, _Dbase, _Expr1 <= _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) <= eval(_Schema, _Dbase, _Expr2))
 [31] eval(_Schema, _Dbase, _Expr1 & _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) & eval(_Schema, _Dbase, _Expr2))
 [32] eval(_Schema, _Dbase, _Expr1 | _Expr2) =
      (eval(_Schema, _Dbase, _Expr1) | eval(_Schema, _Dbase, _Expr2))
 [33] eval(_Schema, _Dbase, btos(_Expr)) =
      btos(eval(_Schema, _Dbase, _Expr))
 [34] eval(_Schema, _Dbase, itos(_Expr)) =
      itos(eval(_Schema, _Dbase, _Expr))
 [35] eval(_Schema, _Dbase, rtos(_Expr)) =
      rtos(eval(_Schema, _Dbase, _Expr))
 [36] eval(_Schema, _Dbase, itor(_Expr)) =
      itor(eval(_Schema, _Dbase, _Expr))
 [37] eval(_Schema, _Dbase, _ExprTup @ _Rel) =
      _ExprTup @ erel(_Schema, _Dbase, _Rel)
 [38] eval(_Schema, _Dbase, # _Rel) =
      # erel(_Schema, _Dbase, _Rel)
 [39] eval(_Schema, _Dbase, sum(_Rel)) =
      sum(erel(_Schema, _Dbase, _Rel))
 [40] eval(_Schema, _Dbase, inf(_Rel)) =
      inf(erel(_Schema, _Dbase, _Rel))
 [41] eval(_Schema, _Dbase, sup(_Rel)) =
      sup(erel(_Schema, _Dbase, _Rel))

 [42] erel(_Schema, _Dbase, {_ExprTup <- @ _Rel | _Expr}) =
      erel(_Schema, _Dbase, {_ExprTup <- attrs(_Schema, _Rel) @ _Rel | _Expr})
 [43] erel(_Schema, _Dbase, {             @ _Rel | _Expr}) =
      erel(_Schema, _Dbase, {             attrs(_Schema, _Rel) @ _Rel | _Expr})

 [44] attrs(_Schema, _Var # _Rel) =
      <_Vars1, _Vars2>
      when attrs(_Schema, _Var) = <_Vars1>,
           attrs(_Schema, _Rel) = <_Vars2>
 [45] attrs(schema , _Var) = <>
 [46] attrs(schema _RDef _RDef*, _Var) =
      <_Vars1, _Vars2, _Vars3>
      when attrs(_RDef, _Var) = <_Vars1>,
           attrs(schema _RDef*, _Var) = <_Vars2>,
           attrs(schema _RDef*, _Var) = <_Vars3>
 [47] attrs(_Var == {_VarTup @ _Rel}, _Var') = _VarTup
      when _Var = _Var'
 [48] attrs(_Var == {_VarTup @ _Rel}, _Var') = <>
      when _Var != _Var'
 [49] attrs(_Var <= {_VarTup @ _Rel}, _Var') = _VarTup
      when _Var = _Var'
 [50] attrs(_Var <= {_VarTup @ _Rel}, _Var') = <>
      when _Var != _Var'

end RDBS
```

```
module Lex_and_Names

exports

  sorts
    Ident
    Unsigned
    Literal
    NumericLit
    ExactLit
    ApproxLit
    StringLit
    %% StringElement
    TableName
    AuthorIdent
    TableIdent
    ColumnName
    CorrelationName
    ModuleName
    CursorName
    ProcedureName
    ParameterName
    EmbeddedVarName

  lexical syntax
    [ \n]                          -> LAYOUT
    "--" ~[\n]* "\n"               -> LAYOUT

    [A-Z][_A-Z0-9]*                -> Ident

    [0-9]+                         -> Unsigned

    %% "'" StringElement + "'"     -> StringLit
    %% ~['\n]                      -> StringElement
    %% "''"                        -> StringElement
    "'" ~['\n]+ "'"                -> StringLit

    "+" Unsigned                   -> ExactLit
    "-" Unsigned                   -> ExactLit
    Unsigned                       -> ExactLit
    "+" Unsigned "." Unsigned      -> ExactLit
    "-" Unsigned "." Unsigned      -> ExactLit
    Unsigned "." Unsigned          -> ExactLit
    "+" Unsigned "."               -> ExactLit
    "-" Unsigned "."               -> ExactLit
    Unsigned "."                   -> ExactLit
    "+" "." Unsigned               -> ExactLit
    "-" "." Unsigned               -> ExactLit
    "." Unsigned                   -> ExactLit

    ExactLit "E" "+" Unsigned      -> ApproxLit
    ExactLit "E" "-" Unsigned      -> ApproxLit
    ExactLit "E" Unsigned          -> ApproxLit

  context-free syntax
    StringLit                      -> Literal
    NumericLit                     -> Literal
    ExactLit                       -> NumericLit
    ApproxLit                      -> NumericLit

    %% Names

    AuthorIdent "." TableIdent     -> TableName
    TableIdent                     -> TableName
    Ident                          -> AuthorIdent
    Ident                          -> TableIdent
    Ident                          -> ColumnName
    Ident                          -> CorrelationName
    Ident                          -> ModuleName
    Ident                          -> CursorName
    Ident                          -> ProcedureName
    Ident                          -> ParameterName
    ":" Ident                      -> EmbeddedVarName %% see Annex A

  variables
    "_Ident"[0-9']*                -> Ident
    "_Ident*"[0-9']*               -> Ident*
    "_Unsigned"                    -> Unsigned
    "_StringLit"                   -> StringLit
    "_ExactLit"                    -> ExactLit
    "_ApproxLit"                   -> ApproxLit
    "_Literal"                     -> Literal
    "_TableName"                   -> TableName
    "_CorrelationName"             -> CorrelationName
    "_ParameterName"[0-9']*        -> ParameterName
    "_EmbeddedVarName"[0-9']*      -> EmbeddedVarName

end Lex_and_Names
```

```
module ValueExpressions

imports
  Lex_and_Names

exports
  sorts
    ValueSpec
    ParameterSpec
    VariableSpec
    TargetSpec
    IndicatorParam
    IndicatorVar
    ColumnSpec
    Qualifier
    SetFuncSpec
    DistinctSetFunc
    AllSetFunc
    ValueExpr
    Term
    Factor
    Primary

  context-free syntax
    %% Value- and Target specification
    ParameterSpec                -> ValueSpec
    VariableSpec                 -> ValueSpec
    Literal                      -> ValueSpec
    "USER"                       -> ValueSpec
    ParameterSpec                -> TargetSpec
    VariableSpec                 -> TargetSpec
    ParameterName IndicatorParam -> ParameterSpec
    ParameterName                -> ParameterSpec
    "INDICATOR" ParameterName    -> IndicatorParam
    EmbeddedVarName IndicatorVar -> VariableSpec
    EmbeddedVarName              -> VariableSpec
    "INDICATOR" EmbeddedVarName -> IndicatorVar

    %% Column Spec
    Qualifier "." ColumnName     -> ColumnSpec
    ColumnName                   -> ColumnSpec
    TableName                    -> Qualifier
    CorrelationName              -> Qualifier

    %% Set function specification
    "COUNT" "(" "*" ")"          -> SetFuncSpec
    DistinctSetFunc              -> SetFuncSpec
    AllSetFunc                   -> SetFuncSpec
    "AVG" "(" "DISTINCT" ColumnSpec ")"          -> DistinctSetFunc
    "MAX" "(" "DISTINCT" ColumnSpec ")"          -> DistinctSetFunc
    "MIN" "(" "DISTINCT" ColumnSpec ")"          -> DistinctSetFunc
    "SUM" "(" "DISTINCT" ColumnSpec ")"          -> DistinctSetFunc
    "COUNT" "(" "DISTINCT" ColumnSpec ")"        -> DistinctSetFunc
    "AVG" "(" "ALL" ValueExpr ")"                -> AllSetFunc
    "MAX" "(" "ALL" ValueExpr ")"                -> AllSetFunc
    "MIN" "(" "ALL" ValueExpr ")"                -> AllSetFunc
    "SUM" "(" "ALL" ValueExpr ")"                -> AllSetFunc
    "AVG" "(" ValueExpr ")"                      -> AllSetFunc
    "MAX" "(" ValueExpr ")"                      -> AllSetFunc
    "MIN" "(" ValueExpr ")"                      -> AllSetFunc
    "SUM" "(" ValueExpr ")"                      -> AllSetFunc

    %% Value expression
    Term                         -> ValueExpr
    ValueExpr "+" Term           -> ValueExpr
    ValueExpr "-" Term           -> ValueExpr
    Factor                       -> Term
    Term "*" Factor              -> Term
    Term "/" Factor              -> Term
    "+" Primary                  -> Factor
    "-" Primary                  -> Factor
    Primary                      -> Factor
    ValueSpec                    -> Primary
    ColumnSpec                   -> Primary
    SetFuncSpec                  -> Primary
    "(" ValueExpr ")"            -> Primary

  variables
    "_ValueExpr"[0-9']*          -> ValueExpr
    "_Term"[0-9']*               -> Term
    "_Factor"[0-9']*             -> Factor
    "_Primary"[0-9']*            -> Primary
    "_ValueSpec"[0-9']*          -> ValueSpec
    "_ColumnSpec"[0-9']*         -> ColumnSpec
    "_ColumnSpec+"               -> {ColumnSpec ","}+
    "_ParameterSpec"             -> ParameterSpec
    "_VariableSpec"              -> VariableSpec
    "_SetFuncSpec"               -> SetFuncSpec

end ValueExpressions
```

```
module Predicates

imports
  ValueExpressions
  %% QuerySpecs

exports
  sorts
    Predicate
    CompPredicate
    CompOp
    BetweenPredicate
    InPredicate
    InValueList
    LikePredicate
    Pattern
    EscapeChar
    NullPredicate
    QuantifiedPredicate
    Quantifier
    All
    Some
    ExistsPredicate
    SubQuery        %% See QuerySpecs for definition.

  context-free syntax
    %% Predicate
    CompPredicate               -> Predicate
    BetweenPredicate            -> Predicate
    InPredicate                 -> Predicate
    LikePredicate               -> Predicate
    NullPredicate               -> Predicate
    QuantifiedPredicate         -> Predicate
    ExistsPredicate             -> Predicate

    %% Comp predicate
    ValueExpr CompOp ValueExpr  -> CompPredicate
    ValueExpr CompOp SubQuery   -> CompPredicate
    "="                         -> CompOp
    "<>"                        -> CompOp
    "<"                         -> CompOp
    ">"                         -> CompOp
    "<="                        -> CompOp
    ">="                        -> CompOp

    %% Between predicate
    ValueExpr "NOT" "BETWEEN" ValueExpr "AND" ValueExpr -> BetweenPredicate
    ValueExpr       "BETWEEN" ValueExpr "AND" ValueExpr -> BetweenPredicate

    %% In predicate
    ValueExpr "NOT" "IN" SubQuery       -> InPredicate
    ValueExpr "NOT" "IN" InValueList    -> InPredicate
    ValueExpr       "IN" SubQuery       -> InPredicate
    ValueExpr       "IN" InValueList    -> InPredicate
    { ValueSpec "," } +         -> InValueList

    %% Like predicate
    ColumnSpec "NOT" "LIKE" Pattern "ESCAPE" EscapeChar -> LikePredicate
    ColumnSpec "NOT" "LIKE" Pattern                     -> LikePredicate
    ColumnSpec       "LIKE" Pattern "ESCAPE" EscapeChar -> LikePredicate
    ColumnSpec       "LIKE" Pattern                     -> LikePredicate
    ValueSpec                   -> Pattern
    ValueSpec                   -> EscapeChar

    %% Null predicate
    ColumnSpec "IS" "NOT" "NULL"        -> NullPredicate
    ColumnSpec "IS" "NULL"              -> NullPredicate

    %% Quantified predicate
    ValueExpr CompOp Quantifier SubQuery        -> QuantifiedPredicate
    All                         -> Quantifier
    Some                        -> Quantifier
    "ALL"                       -> All
    "SOME"                      -> Some
    "ANY"                       -> Some

    %% Exists predicate
    "EXISTS" SubQuery           -> ExistsPredicate

  variables
    "_Predicate"                -> Predicate
    "_CompOp"                   -> CompOp
    "_InValueList"              -> InValueList
    "_ValueSpec+"               -> {ValueSpec ","}+
    "_Pattern"                  -> Pattern
    "_EscapeChar"               -> EscapeChar
    "_Quantifier"               -> Quantifier

end Predicates
```

```
module QuerySpecs
imports
  Lex_and_Names
  ValueExpressions
  Predicates
exports
  sorts
    SearchCondition
    BooleanTerm
    BooleanFactor
    BooleanPrimary
    TableExpr
    FromClause
    TableReference
    WhereClause
    GroupByClause
    HavingClause
    %% SubQuery    : declared in Predicates.
    ResultSpec
    QuerySpec
    SelectList
  context-free syntax
    %% Search condition
    BooleanTerm                              -> SearchCondition
    SearchCondition "OR" BooleanTerm         -> SearchCondition
    BooleanFactor                            -> BooleanTerm
    BooleanTerm "AND" BooleanFactor          -> BooleanTerm
    "NOT" BooleanPrimary                     -> BooleanFactor
    BooleanPrimary                           -> BooleanFactor
    Predicate                                -> BooleanPrimary
    "(" SearchCondition ")"                  -> BooleanPrimary

    %% Table expression
    FromClause WhereClause GroupByClause HavingClause   -> TableExpr
    FromClause WhereClause GroupByClause                -> TableExpr
    FromClause WhereClause HavingClause                 -> TableExpr
    FromClause WhereClause                              -> TableExpr
    FromClause GroupByClause HavingClause               -> TableExpr
    FromClause GroupByClause                            -> TableExpr
    FromClause HavingClause                             -> TableExpr
    FromClause                                          -> TableExpr

    %% From clause
    "FROM" { TableReference "," } +      -> FromClause
    TableName CorrelationName            -> TableReference
    TableName                            -> TableReference

    %% Where clause
    "WHERE" SearchCondition              -> WhereClause

    %% Group by clause
    "GROUP" "BY" { ColumnSpec "," } +    -> GroupByClause

    %% Having clause
    "HAVING" SearchCondition             -> HavingClause

    %% Subquery
    "(" "SELECT" "ALL"      ResultSpec TableExpr ")"    -> SubQuery
    "(" "SELECT" "DISTINCT" ResultSpec TableExpr ")"    -> SubQuery
    "(" "SELECT"            ResultSpec TableExpr ")"    -> SubQuery
    ValueExpr                            -> ResultSpec
    "*"                                  -> ResultSpec

    %% Query specification
    "SELECT" "ALL" SelectList TableExpr         -> QuerySpec
    "SELECT" "DISTINCT" SelectList TableExpr    -> QuerySpec
    "SELECT" SelectList TableExpr               -> QuerySpec
    { ValueExpr "," } +                  -> SelectList
    "*"                                  -> SelectList

  variables
    "_QuerySpec"                -> QuerySpec
    "_SubQuery"                 -> SubQuery
    "_ResultSpec"               -> ResultSpec
    "_SelectList"               -> SelectList
    "_ValueExpr+"               -> {ValueExpr ","}+
    "_TableExpr"                -> TableExpr
    "_FromClause"               -> FromClause
    "_WhereClause"              -> WhereClause
    "_GroupByClause"            -> GroupByClause
    "_HavingClause"             -> HavingClause
    "_TableRefList"             -> {TableReference ","}+
    "_SearchCondition"          -> SearchCondition
    "_BooleanTerm"              -> BooleanTerm
    "_BooleanFactor"            -> BooleanFactor
    "_BooleanPrimary"           -> BooleanPrimary
    "_ColumnSpecList"           -> {ColumnSpec ","}*
    "_TableRef"                 -> TableReference
    "_TableRef+"                -> {TableReference ","}+
end QuerySpecs
```

```
module DataTypes

imports

  Lex_and_Names

exports

  sorts

    DataType
    StringType
    ExactType
    ApproxType
    Length
    Precision
    Scale

  context-free syntax

    %% DataType

    StringType                  -> DataType
    ExactType                   -> DataType
    ApproxType                  -> DataType

    "CHARACTER" "(" Length ")"  -> StringType
    "CHARACTER"                 -> StringType
    "CHAR" "(" Length ")"       -> StringType
    "CHAR"                      -> StringType

    "NUMERIC" "(" Precision "," Scale ")"       -> ExactType
    "NUMERIC" "(" Precision ")"                 -> ExactType
    "NUMERIC"                                   -> ExactType
    "DECIMAL" "(" Precision "," Scale ")"       -> ExactType
    "DECIMAL" "(" Precision ")"                 -> ExactType
    "DECIMAL"                                   -> ExactType
    "DEC" "(" Precision "," Scale ")"           -> ExactType
    "DEC" "(" Precision ")"                     -> ExactType
    "DEC"                                       -> ExactType
    "INTEGER"                                   -> ExactType
    "INT"                                       -> ExactType
    "SMALLINT"                                  -> ExactType

    "FLOAT" "(" Precision ")"   -> ApproxType
    "FLOAT"                     -> ApproxType
    "REAL"                      -> ApproxType
    "DOUBLE" "PRECISION"        -> ApproxType

    Unsigned                    -> Length
    Unsigned                    -> Precision
    Unsigned                    -> Scale

  variables

    "_Length"[0-9']*            -> Length
    "_Precision"[0-9']*         -> Precision
    "_Scale"[0-9']*             -> Scale

equations

[5-05-SR-1] CHAR = CHARACTER
[5-05-SR-1] CHAR(_Length) = CHARACTER(_Length)
[5-05-SR-1] DEC = DECIMAL
[5-05-SR-1] DEC(_Precision) = DECIMAL(_Precision)
[5-05-SR-1] DEC(_Precision, _Scale) = DECIMAL(_Precision, _Scale)
[5-05-SR-1] INT = INTEGER

[5-05-SR-3] CHARACTER = CHARACTER(1)
[5-05-SR-3] NUMERIC = NUMERIC(13)
[5-05-SR-3] DECIMAL = DECIMAL(13)
[5-05-SR-3] FLOAT = FLOAT(13)
[5-05-SR-3] NUMERIC(_Precision) = NUMERIC(_Precision, 0)
[5-05-SR-3] DECIMAL(_Precision) = DECIMAL(_Precision, 0)

end DataTypes
```

```
module Schemas

imports

  Lex_and_Names
  DataTypes
  QuerySpecs

exports

  sorts

    Environment
    Schema
    SchemaAuthorClause
    SchemaAuthorIdent
    SchemaElement
    TableDef
    TableElement
    ColumnDef
    ColumnConstr
    DefaultClause
    TableConstrDef
    UniqueConstrDef
    UniqueSpec
    UniqueColumnList
    ReferentialConstrDef
    ReferencesSpec
    ReferencingColumns
    ReferencedTableAndColumns
    ReferenceColumnList
    CheckConstrDef
    ViewDef
    ViewColumnList
    PrivilegeDef
    Privileges
    Action
    GrantColumnList
    Grantee

  context-free syntax

    %% Environment

    "CREATE" "ENVIRONMENT" Ident Schema*                -> Environment

    %% Schema

    "CREATE" "SCHEMA" SchemaAuthorClause SchemaElement* -> Schema
    "AUTHORIZATION" SchemaAuthorIdent                   -> SchemaAuthorClause
    AuthorIdent                                         -> SchemaAuthorIdent

    TableDef                    -> SchemaElement
    ViewDef                     -> SchemaElement
    PrivilegeDef                -> SchemaElement

    %% Table Def

    "CREATE" "TABLE" TableName "("{TableElement","}+")" -> TableDef

    ColumnDef                   -> TableElement
    TableConstrDef              -> TableElement

    %% Column Def

    ColumnName DataType DefaultClause ColumnConstr*     -> ColumnDef
    ColumnName DataType ColumnConstr*                   -> ColumnDef

    "NOT" "NULL" UniqueSpec             -> ColumnConstr
    "NOT" "NULL"                        -> ColumnConstr
    ReferencesSpec                      -> ColumnConstr
    "CHECK" "(" SearchCondition ")"     -> ColumnConstr

    %% Default Clause

    "DEFAULT" Literal                   -> DefaultClause
    "DEFAULT" "USER"                    -> DefaultClause
    "DEFAULT" "NULL"                    -> DefaultClause

    %% Table Constr Def

    UniqueConstrDef                     -> TableConstrDef
    ReferentialConstrDef                -> TableConstrDef
    CheckConstrDef                      -> TableConstrDef

    %% Unique Constr Def

    UniqueSpec "(" UniqueColumnList ")" -> UniqueConstrDef
    "UNIQUE"                            -> UniqueSpec
    "PRIMARY" "KEY"                     -> UniqueSpec
```

```
    { ColumnName "," }+                 -> UniqueColumnList

    %% Referential Constr Def

    "FOREIGN" "KEY" "(" ReferencingColumns ")" ReferencesSpec   -> ReferentialConstrDef
    "REFERENCES" ReferencedTableAndColumns                      -> ReferencesSpec
    ReferenceColumnList                                         -> ReferencingColumns
    TableName "(" ReferenceColumnList ")"                       -> ReferencedTableAndColumns
    TableName                                                   -> ReferencedTableAndColumns
    { ColumnName "," } *                                        -> ReferenceColumnList

    %% Check Constr Def

    "CHECK" "(" SearchCondition ")"     -> CheckConstrDef

    %% View Def

    "CREATE" "VIEW" TableName "(" ViewColumnList ")"
    "AS" QuerySpec "WITH" "CHECK" "OPTION"              -> ViewDef
    "CREATE" "VIEW" TableName "(" ViewColumnList ")"
    "AS" QuerySpec                                      -> ViewDef
    "CREATE" "VIEW" TableName
    "AS" QuerySpec "WITH" "CHECK" "OPTION"              -> ViewDef
    "CREATE" "VIEW" TableName
    "AS" QuerySpec                                      -> ViewDef

    { ColumnName "," }+                 -> ViewColumnList

    %% Privilege Def

    "GRANT" Privileges "ON" TableName
    "TO" { Grantee "," }* "WITH" "GRANT" "OPTION"       -> PrivilegeDef
    "GRANT" Privileges
    "ON" TableName "TO" { Grantee "," }*                -> PrivilegeDef

    "ALL" "PRIVILEGES"                  -> Privileges
    { Action "," }*                     -> Privileges

    "SELECT"                            -> Action
    "INSERT"                            -> Action
    "DELETE"                            -> Action
    "UPDATE" "(" GrantColumnList ")"    -> Action
    "UPDATE"                            -> Action

    { ColumnName "," } *                -> GrantColumnList

    "PUBLIC"                            -> Grantee
    AuthorIdent                         -> Grantee

  variables
    "_Environment"                      -> Environment
    "_Schema"                           -> Schema
    "_Schema*"                          -> Schema*
    "_SchemaElement"                    -> SchemaElement
    "_SchemaElement*"                   -> SchemaElement*
    "_TableElement"                     -> TableElement
    "_TableElement+"                    -> {TableElement ","}+
    "_TableDef"                         -> TableDef
    "_ViewDef"                          -> ViewDef
    "_PrivilegeDef"                     -> PrivilegeDef
    "_ColumnDef"                        -> ColumnDef
    "_TableConstrDef"                   -> TableConstrDef
    "_ViewColumnList"                   -> ViewColumnList
    "_QuerySpec"                        -> QuerySpec
    "_Privileges"                       -> Privileges
    "_GranteeList"                      -> {Grantee ","}*
    "_Grantee"                          -> Grantee
    "_Grantee*"                         -> Grantee*
    "_ColumnName"                       -> ColumnName
    "_ColumnName+"                      -> {ColumnName ","}+
    "_DataType"                         -> DataType
    "_DefaultClause"                    -> DefaultClause
    "_ColumnConstr*"                    -> ColumnConstr*
    "_StringType"                       -> StringType
    "_ExactType"                        -> ExactType
    "_ApproxType"                       -> ApproxType
    "_Literal"                          -> Literal
    "_UniqueConstrDef"                  -> UniqueConstrDef
    "_ReferentialConstrDef"             -> ReferentialConstrDef
    "_CheckConstrDef"                   -> CheckConstrDef

end Schemas
```

```
module DataManipulation

imports

  QuerySpecs
  DataTypes

exports

  sorts

    CloseStat
    CommitStat
    DeclareCursor
    CursorSpec
    QueryExpr
    QueryTerm
    OrderByClause
    SortSpec
    DeleteStatPositioned
    DeleteStatSearched
    FetchStat
    FetchTargetList
    InsertStat
    InsertColumnList
    InsertValueList
    InsertValue
    OpenStat
    RollbackStat
    SelectStat
    SelectTargetList
    UpdateStatPositioned
    SetClausePositioned
    ObjectColumnPositioned
    UpdateStatSearched
    SetClauseSearched
    ObjectColumnSearched

 context-free syntax

   %% Data manipulation Language

   %% Close Stat

   "CLOSE" CursorName                    -> CloseStat

   %% Commit Stat

   "COMMIT" "WORK"                       -> CommitStat

   %% Declare Cursor

   "DECLARE" CursorName "CURSOR" "FOR" CursorSpec      -> DeclareCursor

   QueryExpr OrderByClause               -> CursorSpec
   QueryExpr                             -> CursorSpec

   QueryTerm                             -> QueryExpr
   QueryExpr "UNION" "ALL" QueryTerm     -> QueryExpr
   QueryExpr "UNION" QueryTerm           -> QueryExpr

   QuerySpec                             -> QueryTerm
   "(" QueryExpr ")"                     -> QueryTerm

   "ORDER" "BY" {SortSpec ","}*          -> OrderByClause

   Unsigned "ASC"                        -> SortSpec
   Unsigned "DESC"                       -> SortSpec
   Unsigned                              -> SortSpec
   ColumnSpec "ASC"                      -> SortSpec
   ColumnSpec "DESC"                     -> SortSpec
   ColumnSpec                            -> SortSpec

   %% Delete Stat Positioned

   "DELETE" "FROM" TableName
   "WHERE" "CURRENT" "OF" CursorName                   -> DeleteStatPositioned

   %% Delete Stat Searched

   "DELETE" "FROM" TableName "WHERE" SearchCondition   -> DeleteStatSearched
   "DELETE" "FROM" TableName                           -> DeleteStatSearched

   %% Fetch Stat

   "FETCH" CursorName "INTO" FetchTargetList           -> FetchStat

   {TargetSpec ","}*                     -> FetchTargetList
   {ParameterSpec ","}*                  -> FetchTargetList
```

```
    %% Insert Stat

    "INSERT" "INTO" TableName "(" InsertColumnList ")"
    "VALUES" "(" InsertValueList ")"                                    -> InsertStat
    "INSERT" "INTO" TableName "(" InsertColumnList ")" QuerySpec        -> InsertStat
    "INSERT" "INTO" TableName
    "VALUES" "(" InsertValueList ")"                                    -> InsertStat
    "INSERT" "INTO" TableName QuerySpec                                 -> InsertStat

    {ColumnName ","}*                   -> InsertColumnList

    {InsertValue ","}*                  -> InsertValueList
    ValueSpec                           -> InsertValue
    "NULL"                              -> InsertValue

    %% Open Stat

    "OPEN" CursorName                   -> OpenStat

    %% Rollback Stat

    "ROLLBACK" "WORK"                   -> RollbackStat

    %% Select Stat

    "SELECT" "ALL" SelectList "INTO" SelectTargetList TableExpr         -> SelectStat
    "SELECT" "DISTINCT" SelectList "INTO" SelectTargetList TableExpr    -> SelectStat
    "SELECT" SelectList "INTO" SelectTargetList TableExpr               -> SelectStat

    {TargetSpec ","}*                   -> SelectTargetList
    {ParameterSpec ","}*                -> SelectTargetList

    %% Update Stat Positioned

    "UPDATE" TableName "SET" {SetClausePositioned ","}*
    "WHERE" "CURRENT" "OF" CursorName                                   -> UpdateStatPositioned

    ObjectColumnPositioned "=" ValueExpr                                -> SetClausePositioned
    ObjectColumnPositioned "=" "NULL"                                   -> SetClausePositioned

    ColumnName                          -> ObjectColumnPositioned

    %% Update Stat Searched

    "UPDATE" TableName "SET" {SetClauseSearched ","}* "WHERE" SearchCondition   -> UpdateStatSearched
    "UPDATE" TableName "SET" {SetClauseSearched ","}*                           -> UpdateStatSearched

    ObjectColumnSearched "=" ValueExpr  -> SetClauseSearched
    ObjectColumnSearched "=" "NULL"     -> SetClauseSearched

    ColumnName                          -> ObjectColumnSearched


end DataManipulation
```

```
module Modules

imports

  Lex_and_Names
  DataTypes
  DataManipulation

exports

  sorts

    Module
    LanguageClause
    ModuleAuthorClause
    ModuleAuthorIdent
    ModuleNameClause
    Procedure
    ParamDeclaration
    SQLCODEParam
    SQLStat

  context-free syntax

    %% Module Language

    %% Module

    ModuleNameClause
    LanguageClause
    ModuleAuthorClause
    DeclareCursor*
    Procedure+                          -> Module

    "LANGUAGE" "COBOL"                  -> LanguageClause
    "LANGUAGE" "FORTRAN"                -> LanguageClause
    "LANGUAGE" "PASCAL"                 -> LanguageClause
    "LANGUAGE" "PLI"                    -> LanguageClause

    "AUTHORIZATION" ModuleAuthorIdent   -> ModuleAuthorClause
    AuthorIdent                         -> ModuleAuthorIdent

    %% Module Name Clause

    "MODULE" ModuleName                 -> ModuleNameClause
    "MODULE"                            -> ModuleNameClause

    %% Procedure

    "PROCEDURE" ProcedureName ParamDeclaration+ ";" SQLStat ";" -> Procedure

    ParameterName DataType              -> ParamDeclaration
    SQLCODEParam                        -> ParamDeclaration
    "SQLCODE"                           -> SQLCODEParam

    CloseStat                           -> SQLStat
    CommitStat                          -> SQLStat
    DeleteStatPositioned                -> SQLStat
    DeleteStatSearched                  -> SQLStat
    FetchStat                           -> SQLStat
    InsertStat                          -> SQLStat
    OpenStat                            -> SQLStat
    RollbackStat                        -> SQLStat
    SelectStat                          -> SQLStat
    UpdateStatPositioned                -> SQLStat
    UpdateStatSearched                  -> SQLStat

end Modules



module SQL

imports

  Schemas
  QuerySpecs
  Modules


end SQL
```

```
module Errors

imports

  Layout

exports

  sorts

    ERROR

  lexical syntax

    "OK"                          -> ERROR
    "ERROR!"                      -> ERROR

  context-free syntax

    ERROR "AND" ERROR             -> ERROR {right}
    ERROR "AND" "THEN" ERROR      -> ERROR {right}
    "(" ERROR ")"                 -> ERROR

  variables

    "_Error"[0-9']*               -> ERROR

equations

[err1] OK AND _Error = _Error
[err2] _Error AND OK = _Error

[err3] OK AND THEN _Error = _Error
[err4] _Error1 AND THEN _Error2 = _Error1

[err5] (_Error) = _Error

end Errors
```

```
module SchemaDescr

imports

  Layout
  Booleans
  Integers
  Schemas

exports

  sorts

    EnvDescr            %% Environment
    SListDescr          %% Schema*
    SDescr              %% Schema
    TVListDescr         %% (Table|View)Def*
    TVDescr             %% (Table|View)Def

    ColListDescr        %% ColumnDef*
    ColDescr            %% ColumnDef
    DTDescr             %% DataType
    TypDescr            %% Type
    DefDescr            %% DefaultClause
    CConListDescr       %% ColumnConstr*
    TConListDescr       %% TableConstrDef*
    TConDescr           %% TableConstrDef

    IdentList           %% ViewColumnDescr*, ... .

    PListDescr          %% PrivilegeDef*
    PDescr              %% PrivilegeDef
    GListDescr          %% Grantee*

  context-free syntax

    "_"                 -> Ident  %% for use of 'un-named' column (hidden for user)

    "<" Ident "," SListDescr ">"                                          -> EnvDescr
    "[" SDescr* "]"                                                       -> SListDescr
    "<" Ident "," TVListDescr "," PListDescr ">"                          -> SDescr
    "[" TVDescr* "]"                                                      -> TVListDescr

    %% Table Description
    "<" Ident "," Ident "," ColListDescr "," TConListDescr ">"            -> TVDescr
    "[" ColDescr* "]"                                                     -> ColListDescr
    "<" Ident "," DTDescr "," DefDescr "," CConListDescr "," BOOL ">"     -> ColDescr
    "<" TypDescr "," INT "," INT ">"                                      -> DTDescr
    "String"                                                              -> TypDescr
    "Exact"                                                               -> TypDescr
    "Approx"                                                              -> TypDescr
    "Notype"                                                              -> TypDescr
    Literal                                                               -> DefDescr
    "USER"                                                                -> DefDescr
    "NULL"                                                                -> DefDescr
    "[" ColumnConstr* "]"                                                 -> CConListDescr
    "[" TConDescr* "]"                                                    -> TConListDescr
    "<" UniqueConstrDef "," ReferentialConstrDef "," CheckConstrDef ">"   -> TConDescr

    %% View Description
    "<" Ident "," Ident "," IdentList "," QuerySpec "," BOOL ">"          -> TVDescr
    "[" Ident* "]"                                                        -> IdentList

    %% Privilege Description
    "[" PDescr* "]"                                                       -> PListDescr
    "<" Privileges "," Ident "," Ident "," GListDescr "," BOOL ">"        -> PDescr
    "[" Grantee* "]"                                                      -> GListDescr

    env-descr "(" Environment ")"                                         -> EnvDescr

    %% auxilary functions for using the description:

    lookup-table "(" TableName "," EnvDescr ")"          -> TVListDescr
    lookup-table "(" TableName "," SDescr   ")"          -> TVListDescr
    lookup-table "(" TableName "," TVListDescr  ")"      -> TVListDescr
    lookup-table "(" TableName "," TVDescr  ")"          -> TVListDescr

    eq-table-name "(" TableName "," TableName ")"        -> BOOL
    eq-table-id   "(" TableIdent "," TableIdent ")"      -> BOOL

    correname       "(" CorrelationName "," TVDescr ")"  -> TVDescr
    combine-tables "(" TVListDescr "," TVListDescr ")"   -> TVListDescr
    append-table    "(" TVListDescr "," TVDescr ")"      -> TVListDescr

    set-group-column  "(" ColumnSpec "," TVListDescr ")"         -> TVListDescr
    set-group-column  "(" ColumnSpec "," TVDescr ")"             -> TVDescr
    set-group-column1 "(" ColumnSpec "," ColListDescr ")"        -> ColListDescr
    set-group-column1 "(" ColumnSpec "," ColDescr ")"            -> ColDescr

    lookup-column  "(" ColumnSpec "," TVListDescr ")"    -> ColListDescr
```

```
    lookup-column  "(" ColumnSpec "," TVDescr ")"        -> ColListDescr
    lookup-column1 "(" ColumnSpec "," ColListDescr ")"   -> ColListDescr
    lookup-column1 "(" ColumnSpec "," ColDescr ")"       -> ColListDescr

  variables

    "_EnvDescr"[0-9']*          -> EnvDescr
    "_SListDescr"               -> SListDescr
    "_SDescr*"[0-9']*           -> SDescr*
    "_SDescr"[0-9']*            -> SDescr
    "_TVListDescr"[0-9']*       -> TVListDescr
    "_TVDescr+"                 -> TVDescr+
    "_TVDescr*"[0-9']*          -> TVDescr*
    "_TVDescr"[0-9']*           -> TVDescr

    "_ColListDescr"             -> ColListDescr
    "_ColDescr+"                -> ColDescr+
    "_ColDescr*"[0-9']*         -> ColDescr*
    "_ColDescr"[0-9']*          -> ColDescr
    "_DTDescr"[0-9']*           -> DTDescr
    "_TypDescr"[0-9']*          -> TypDescr
    "_DefDescr"                 -> DefDescr
    "_CConListDescr"            -> CConListDescr
    "_TConListDescr"            -> TConListDescr
    "_TConDescr*"               -> TConDescr*
    "_TConDescr"                -> TConDescr

    "_IdentList"                -> IdentList

    "_PListDescr"[0-9']*        -> PListDescr
    "_PDescr*"                  -> PDescr*
    "_PDescr"                   -> PDescr

hiddens

  context-free syntax

    sl-descr  "(" Schema* ")"                       -> SListDescr
    s-descr   "(" Schema ")"                        -> SDescr

    tvl-descr   "(" Ident "," SchemaElement* ")"    -> TVListDescr
    tv-descr    "(" Ident "," SchemaElement ")"     -> TVDescr

    coll-descr  "(" {TableElement ","}+ ")"         -> ColListDescr
    col-descr   "(" ColumnDef ")"                   -> ColDescr
    dt-descr    "(" DataType ")"                    -> DTDescr
    type        "(" DataType ")"                    -> TypDescr
    length      "(" DataType ")"                    -> Unsigned
    scale       "(" DataType ")"                    -> Unsigned
    default     "(" DefaultClause ")"               -> DefDescr
    ccl-descr   "(" ColumnConstr* ")"               -> CConListDescr
    tconl-descr "(" {TableElement ","}+ ")"         -> TConListDescr
    tcon-descr  "(" TableConstrDef ")"              -> TConDescr

    idl-descr   "(" ViewColumnList ")"              -> IdentList

    pl-descr    "(" Ident "," SchemaElement* ")"    -> PListDescr
    p-descr     "(" Ident "," PrivilegeDef ")"      -> PDescr
    gl-descr    "(" {Grantee ","}* ")"              -> GListDescr

    unsigned2int "(" Unsigned ")"                   -> INT

equations

[env1  ] env-descr(CREATE ENVIRONMENT _Ident _Schema*) =
           <_Ident, sl-descr(_Schema*)>

[sl1   ] sl-descr() = []
[sl2   ] sl-descr(_Schema _Schema*) =
           [s-descr(_Schema) _SDescr*]
           when sl-descr(_Schema*) = [_SDescr*]

[s1    ] s-descr(CREATE SCHEMA AUTHORIZATION _Ident _SchemaElement*) =
           <_Ident, tvl-descr(_Ident, _SchemaElement*), pl-descr(_Ident, _SchemaElement*)>

[tvl1  ] tvl-descr(_Ident, ) = []
[tvl2  ] tvl-descr(_Ident, _TableDef _SchemaElement*) =
           [tv-descr(_Ident, _TableDef) _TVDescr*]
           when tvl-descr(_Ident, _SchemaElement*) = [_TVDescr*]
[tvl3  ] tvl-descr(_Ident, _ViewDef _SchemaElement*) =
           [tv-descr(_Ident, _ViewDef) _TVDescr*]
           when tvl-descr(_Ident, _SchemaElement*) = [_TVDescr*]
[tvl4  ] tvl-descr(_Ident, _PrivilegeDef _SchemaElement*) =
           tvl-descr(_Ident, _SchemaElement*)

[tv1   ] tv-descr(_Ident, CREATE TABLE _Ident1._Ident2 ( _TableElement+ )) =
           <_Ident1, _Ident2, coll-descr(_TableElement+), tconl-descr(_TableElement+)>
[tv2   ] tv-descr(_Ident, CREATE TABLE _Ident2 ( _TableElement+ )) =
           <_Ident, _Ident2, coll-descr(_TableElement+), tconl-descr(_TableElement+)>
[tv3   ] tv-descr(_Ident, CREATE VIEW _Ident1._Ident2 ( _ViewColumnList )
```

```
                        AS _QuerySpec WITH CHECK OPTION) =
          <_Ident1, _Ident2, idl-descr(_ViewColumnList), _QuerySpec, true>
[tv4    ] tv-descr(_Ident, CREATE VIEW _Ident1._Ident2 ( _ViewColumnList )
                        AS _QuerySpec) =
          <_Ident1, _Ident2, idl-descr(_ViewColumnList), _QuerySpec, false>
[tv5    ] tv-descr(_Ident, CREATE VIEW _Ident1._Ident2
                        AS _QuerySpec WITH CHECK OPTION) =
          <_Ident1, _Ident2, [], _QuerySpec, true>
[tv6    ] tv-descr(_Ident, CREATE VIEW _Ident1._Ident2
                        AS _QuerySpec) =
          <_Ident1, _Ident2, [], _QuerySpec, false>
[tv7    ] tv-descr(_Ident, CREATE VIEW _Ident2 ( _ViewColumnList )
                        AS _QuerySpec WITH CHECK OPTION) =
          <_Ident, _Ident2, idl-descr(_ViewColumnList), _QuerySpec, true>
[tv8    ] tv-descr(_Ident, CREATE VIEW _Ident2 ( _ViewColumnList )
                        AS _QuerySpec) =
          <_Ident, _Ident2, idl-descr(_ViewColumnList), _QuerySpec, false>
[tv9    ] tv-descr(_Ident, CREATE VIEW _Ident2
                        AS _QuerySpec WITH CHECK OPTION) =
          <_Ident, _Ident2, [], _QuerySpec, true>
[tv10   ] tv-descr(_Ident, CREATE VIEW _Ident2
                        AS _QuerySpec) =
          <_Ident, _Ident2, [], _QuerySpec, false>

[coll1  ] coll-descr(_ColumnDef) =
          [col-descr(_ColumnDef)]
[coll2  ] coll-descr(_TableConstrDef) =
          []
[coll3  ] coll-descr(_ColumnDef, _TableElement+) =
          [col-descr(_ColumnDef) _ColDescr*]
          when coll-descr(_TableElement+) = [_ColDescr*]
[coll4  ] coll-descr(_TableConstrDef, _TableElement+) =
          [_ColDescr*]
          when coll-descr(_TableElement+) = [_ColDescr*]

[col1   ] col-descr(_Ident _DataType _DefaultClause _ColumnConstr*) =
          <_Ident, dt-descr(_DataType), default(_DefaultClause), ccl-descr(_ColumnConstr*), false>
[col2   ] col-descr(_Ident _DataType _ColumnConstr*) =
          <_Ident, dt-descr(_DataType), NULL, ccl-descr(_ColumnConstr*), false>
          %% default "NULL" may be the wrong choise (see 6.3)

[dt1    ] dt-descr(_DataType) =
          <type(_DataType), unsigned2int(length(_DataType)), unsigned2int(scale(_DataType))>

%% type() and scale(): see below.

[def1   ] default(DEFAULT _Literal) = _Literal
[def2   ] default(DEFAULT USER) = USER
[def3   ] default(DEFAULT NULL) = NULL

[ccl1   ] ccl-descr(_ColumnConstr*) = [_ColumnConstr*]

[tconl1] tconl-descr(_ColumnDef) =
          []
[tconl2] tconl-descr(_TableConstrDef) =
          [tcon-descr(_TableConstrDef)]
[tconl3] tconl-descr(_ColumnDef, _TableElement+) =
          [_TConDescr*]
          when tconl-descr(_TableElement+) = [_TConDescr*]
[tconl4] tconl-descr(_TableConstrDef, _TableElement+) =
          [tcon-descr(_TableConstrDef) _TConDescr*]
          when tconl-descr(_TableElement+) = [_TConDescr*]

[tcon1  ] tcon-descr(_UniqueConstrDef _ReferentialConstrDef _CheckConstrDef) =
          <_UniqueConstrDef, _ReferentialConstrDef, _CheckConstrDef>

[idl1   ] idl-descr(_Ident) = [_Ident]
[idl2   ] idl-descr(_Ident, _ColumnName+) =
          [_Ident _Ident*]
          when idl-descr(_ColumnName+) = [_Ident*]
[pl1    ] pl-descr(_Ident, ) = []
[pl2    ] pl-descr(_Ident, _TableDef _SchemaElement*) =
          pl-descr(_Ident, _SchemaElement*)
[pl3    ] pl-descr(_Ident, _ViewDef _SchemaElement*) =
          pl-descr(_Ident, _SchemaElement*)
[pl4    ] pl-descr(_Ident, _PrivilegeDef _SchemaElement*) =
          [p-descr(_Ident, _PrivilegeDef) _PDescr*]
          when pl-descr(_Ident, _SchemaElement*) = [_PDescr*]

[p1     ] p-descr(_Ident, GRANT _Privileges ON _Ident1._Ident2 TO _GranteeList WITH GRANT OPTION) =
          <_Privileges, _Ident1, _Ident2, gl-descr(_GranteeList), true>
[p2     ] p-descr(_Ident, GRANT _Privileges ON _Ident1._Ident2 TO _GranteeList) =
          <_Privileges, _Ident1, _Ident2, gl-descr(_GranteeList), false>
[p3     ] p-descr(_Ident, GRANT _Privileges ON _Ident2 TO _GranteeList WITH GRANT OPTION) =
          <_Privileges, _Ident, _Ident2, gl-descr(_GranteeList), true>
[p4     ] p-descr(_Ident, GRANT _Privileges ON _Ident2 TO _GranteeList) =
          <_Privileges, _Ident, _Ident2, gl-descr(_GranteeList), false>

[gl1    ] gl-descr() = []
[gl2    ] gl-descr(_Grantee, _GranteeList) =
```

```
          [_Grantee _Grantee*]
          when gl-descr(_GranteeList) = [_Grantee*]

%% type(), length() and scale():
%% Als gevolg van de equations van module DataTypes zijn niet alle gevals-
%% onderscheidingen noodzakelijk voor de functies type, length en scale
%% hieronder. Zo wordt bijv op de juiste wijze gereduceerd:
%% length(CHAR) -> length(CHARACTER) -> length(CHARACTER(1)) -> 1

[type1 ] type(_StringType) = String
[type2 ] type(_ExactType)  = Exact
[type3 ] type(_ApproxType) = Approx

[leng1 ] length(CHARACTER(_Length)) = _Length
[leng2 ] length(NUMERIC(_Precision, _Scale)) = _Precision
[leng3 ] length(DECIMAL(_Precision, _Scale)) = _Precision
[leng4 ] length(INTEGER) = 13
[leng5 ] length(SMALLINT) = 7
[leng6 ] length(FLOAT(_Precision)) = _Precision
[leng7 ] length(REAL) = 13
[leng8 ] length(DOUBLE PRECISION) = 26

[scale1] scale(CHARACTER(_Length)) = 0
[scale2] scale(NUMERIC(_Precision, _Scale)) = _Scale
[scale3] scale(DECIMAL(_Precision, _Scale)) = _Scale
[scale4] scale(INTEGER) =  0
[scale5] scale(SMALLINT) = 0
[scale6] scale(FLOAT(_Precision)) = 147
[scale7] scale(REAL) = 147
[scale8] scale(DOUBLE PRECISION) = 147

[un2int] unsigned2int(unsigned(_Char+)) = int_const(_Char+)

%% Auxilary functions for using the descriptions:

[lookt1] lookup-table(_TableName, <_Ident, []>) = []
[lookt2] lookup-table(_TableName, <_Ident, [_SDescr _SDescr*]>) =
          [_TVDescr*1 _TVDescr*2]
          when lookup-table(_TableName, _SDescr) = [_TVDescr*1],
               lookup-table(_TableName, <_Ident, [_SDescr*]>) = [_TVDescr*2]

[lookt3] lookup-table(_TableName, <_Ident, _TVListDescr,  _PListDescr>) =
          lookup-table(_TableName, _TVListDescr)

[lookt4] lookup-table(_TableName, []) = []
[lookt5] lookup-table(_TableName, [_TVDescr _TVDescr*]) =
          [_TVDescr*1 _TVDescr*2]
          when lookup-table(_TableName, _TVDescr) = [_TVDescr*1],
               lookup-table(_TableName, [_TVDescr*]) = [_TVDescr*2]

[lookt6] lookup-table(_TableName, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
          [<_Ident1, _Ident2, _ColListDescr, _TConListDescr>]
          when eq-table-name(_TableName, _Ident1._Ident2) = true
[lookt7] lookup-table(_TableName, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
          []
          when eq-table-name(_TableName, _Ident1._Ident2) = false
[lookt8] lookup-table(_TableName, <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
          [<_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>]
          when eq-table-name(_TableName, _Ident1._Ident2) = true
[lookt9] lookup-table(_TableName, <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
          []
          when eq-table-name(_TableName, _Ident1._Ident2) = false

[eqtn1 ] eq-table-name(_Ident1._Ident2, _Ident3._Ident4) =
          eq-table-id(_Ident1, _Ident3) & eq-table-id(_Ident2, _Ident4)
[eqtn2 ] eq-table-name(_Ident1._Ident2, _Ident4) =
          eq-table-id(_Ident2, _Ident4)
[eqtn3 ] eq-table-name(_Ident2, _Ident3._Ident4) =
          eq-table-id(_Ident2, _Ident4)
[eqtn4 ] eq-table-name(_Ident2, _Ident4) =
          eq-table-id(_Ident2, _Ident4)

[eqti1 ] _Ident1  = _Ident2 ==> eq-table-id(_Ident1, _Ident2) = true
[eqti2 ] _Ident1 != _Ident2 ==> eq-table-id(_Ident1, _Ident2) = false

[lookc1] lookup-column(_ColumnSpec, []) = []
[lookc2] lookup-column(_ColumnSpec, [_TVDescr _TVDescr*]) =
          [_ColDescr*1 _ColDescr*2]
          when lookup-column(_ColumnSpec, _TVDescr) = [_ColDescr*1],
               lookup-column(_ColumnSpec, [_TVDescr*]) = [_ColDescr*2]

[lookc3] lookup-column(_TableName._ColumnName, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
          lookup-column1(_ColumnName, _ColListDescr)
          when eq-table-name(_TableName, _Ident1._Ident2) = true
[lookc4] lookup-column(_TableName._ColumnName, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
          []
          when eq-table-name(_TableName, _Ident1._Ident2) = false
[lookc5] lookup-column(_ColumnName, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
          lookup-column1(_ColumnName, _ColListDescr)
```

```
[lookc6] lookup-column1(_ColumnName, []) = []
[lookc7] lookup-column1(_ColumnName, [_ColDescr _ColDescr*]) =
         [_ColDescr*1 _ColDescr*2]
         when lookup-column1(_ColumnName, _ColDescr) = [_ColDescr*1],
              lookup-column1(_ColumnName, [_ColDescr*]) = [_ColDescr*2]

[lookc8] lookup-column1(_Ident, <_Ident', _DTDescr, _Literal, _CConListDescr, _Bool>) =
         [<_Ident', _DTDescr, _Literal, _CConListDescr, _Bool>]
         when _Ident = _Ident'
[lookc9] lookup-column1(_Ident, <_Ident', _DTDescr, _Literal, _CConListDescr, _Bool>) =
         []
         when _Ident != _Ident'

%% combine-tables(old, new) :
%% combine-tables([A B C], [C D E]) = [C D E A B]
[combl ] combine-tables([], [_TVDescr*]) = [_TVDescr*]
[comb2 ] combine-tables([_TVDescr _TVDescr*1], [_TVDescr*2]) =
         combine-tables([_TVDescr*1], append-table([_TVDescr*2], _TVDescr))

[appt1 ] append-table([_TVDescr*], <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
         [_TVDescr*]
         when lookup-table(_Ident1._Ident2, [_TVDescr*]) != []
[appt2 ] append-table([_TVDescr*], <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
         [_TVDescr* <_Ident1, _Ident2, _ColListDescr, _TConListDescr>]
         when lookup-table(_Ident1._Ident2, [_TVDescr*]) = []
[appt3 ] append-table([_TVDescr*], <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
         [_TVDescr*]
         when lookup-table(_Ident1._Ident2, [_TVDescr*]) != []
[appt4 ] append-table([_TVDescr*], <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
         [_TVDescr* <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>]
         when lookup-table(_Ident1._Ident2, [_TVDescr*]) = []

[sgcol1] set-group-column(_ColumnSpec, []) = []
[sgcol2] set-group-column(_ColumnSpec, [_TVDescr _TVDescr*]) =
         [_TVDescr' _TVDescr*']
         when set-group-column(_ColumnSpec, _TVDescr) = _TVDescr',
              set-group-column(_ColumnSpec, [_TVDescr*]) = [_TVDescr*']

[sgcol3] set-group-column(_TableName._ColumnName, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
         <_Ident1, _Ident2, set-group-column1(_ColumnName, _ColListDescr), _TConListDescr>
         when eq-table-name(_TableName, _Ident1._Ident2) = true
[sgcol4] set-group-column(_TableName._ColumnName, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
         <_Ident1, _Ident2, _ColListDescr, _TConListDescr>
         when eq-table-name(_TableName, _Ident1._Ident2) = false
[sgcol5] set-group-column(_ColumnName, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
         <_Ident1, _Ident2, set-group-column1(_ColumnName, _ColListDescr), _TConListDescr>

[sgcol6] set-group-column1(_Ident, []) = []
[sgcol7] set-group-column1(_Ident, [_ColDescr _ColDescr*]) =
         [_ColDescr' _ColDescr*']
         when set-group-column1(_Ident, _ColDescr) = _ColDescr',
              set-group-column1(_Ident, [_ColDescr*]) = [_ColDescr*']

[sgcol8] set-group-column1(_Ident, <_Ident', _DTDescr, _Literal, _CConListDescr, _Bool>) =
         <_Ident', _DTDescr, _Literal, _CConListDescr, true>
         when _Ident = _Ident'
[sgcol9] set-group-column1(_Ident, <_Ident', _DTDescr, _Literal, _CConListDescr, _Bool>) =
         <_Ident', _DTDescr, _Literal, _CConListDescr, _Bool>
         when _Ident != _Ident'

[corrn1] correname(_Ident, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
         <_Ident1, _Ident, _ColListDescr, _TConListDescr>
[corrn2] correname(_Ident, <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
         <_Ident1, _Ident, _IdentList, _QuerySpec, _Bool>

end SchemaDescr
```

```
module SchemaCheck
imports
  Errors SchemaDescr TC_QueryPred
exports
  context-free syntax
    tc "(" EnvDescr ")"                                  -> ERROR
    expand-env "(" EnvDescr "," EnvDescr ")"             -> EnvDescr
    expand-sch "(" EnvDescr "," SDescr ")"               -> SDescr
    expand-tv  "(" EnvDescr "," TVDescr ")"              -> TVDescr
hiddens
  context-free syntax
    sl-check   "(" EnvDescr "," SListDescr ")"           -> ERROR
    s-check    "(" EnvDescr "," SDescr ")"               -> ERROR
    tvl-check  "(" EnvDescr"," Ident"," TVListDescr ")" -> ERROR
    tv-check   "(" EnvDescr "," TVDescr ")"              -> ERROR
    coll-check "(" ColListDescr ")"                      -> ERROR
    vcoll-check"(" IdentList "," ColListDescr ")"        -> ERROR
    should-provide-viewcolumnlist "(" IdentList "," ColListDescr ")"    -> ERROR
    all-ids-must-be-different     "(" IdentList ")"                      -> ERROR
    right-number-of-viewcolumns   "(" IdentList "," ColListDescr ")"    -> ERROR
    "Schema Id" Ident "should be unique!"                -> ERROR
    "Authorization Id" Ident "should be" Ident "!"       -> ERROR
    "Table Name" Ident "should be unique!"               -> ERROR
    "Column Name" Ident "should be unique!"              -> ERROR
    "Should provide viewcolumnlist!"                     -> ERROR
    "All viewcolumns must be different!"                 -> ERROR
    "Too many viewcolumns specified!"                    -> ERROR
    "Not enough viewcolumns specified!"                  -> ERROR
    schema-id "(" SDescr ")"                             -> Ident
    s-occurs  "(" Ident "," SListDescr ")"               -> BOOL
    author-id "(" TVDescr ")"                            -> Ident
    table-id  "(" TVDescr ")"                            -> Ident
    t-occurs  "(" Ident "," TVListDescr ")"              -> BOOL
    column-id "(" ColDescr ")"                           -> Ident
    c-occurs  "(" Ident "," ColListDescr ")"             -> BOOL
    i-occurs  "(" Ident "," IdentList ")"                -> BOOL
    rename    "(" IdentList "," ColListDescr ")"         -> ColListDescr
equations
[env1  ] tc(<_Ident, _SListDescr>) =
         sl-check(<_Ident, _SListDescr>, _SListDescr)

[sl1   ] sl-check(_EnvDescr, []) = OK
[sl2   ] sl-check(_EnvDescr, [_SDescr*1 _SDescr _SDescr*2]) =  %% volgorde afhankelijk impl!
         Schema Id schema-id(_SDescr) should be unique!
         when s-occurs(schema-id(_SDescr), [_SDescr*1 _SDescr*2]) = true
[sl3   ] sl-check(_EnvDescr, [_SDescr*1 _SDescr _SDescr*2]) =
         s-check(_EnvDescr, _SDescr) AND sl-check(_EnvDescr, [_SDescr*1 _SDescr*2])
         when s-occurs(schema-id(_SDescr), [_SDescr*1 _SDescr*2]) = false

[sid1  ] schema-id(<_Ident, _TVListDescr, _PListDescr>) = _Ident

[socc1 ] s-occurs(_Ident, []) = false
[socc2 ] s-occurs(_Ident, [_SDescr _SDescr*]) = true
         when _Ident = schema-id(_SDescr)
[socc3 ] s-occurs(_Ident, [_SDescr _SDescr*]) =
         s-occurs(_Ident, [_SDescr*])
         when _Ident != schema-id(_SDescr)

  1    ] s-check(_EnvDescr, <_Ident, _TVListDescr, _PListDescr>) =
         tvl-check(_EnvDescr, _Ident, _TVListDescr)

[tvl1  ] tvl-check(_EnvDescr, _Ident, []) = OK
[tvl2  ] tvl-check(_EnvDescr, _Ident, [_TVDescr*1 _TVDescr _TVDescr*2]) =
         Authorization Id author-id(_TVDescr) should be _Ident!
         when author-id(_TVDescr) != _Ident
[tvl3  ] tvl-check(_EnvDescr, _Ident, [_TVDescr*1 _TVDescr _TVDescr*2]) =
         Table Name table-id(_TVDescr) should be unique!
         when t-occurs(table-id(_TVDescr), [_TVDescr*1 _TVDescr*2]) = true
[tvl4  ] tvl-check(_EnvDescr, _Ident, [_TVDescr*1 _TVDescr _TVDescr*2]) =
         tv-check(_EnvDescr, _TVDescr)
         when author-id(_TVDescr) = _Ident,
              t-occurs(table-id(_TVDescr), [_TVDescr*1 _TVDescr*2]) = false

[auth1 ] author-id(<_Ident1, _Ident2, _ColListDescr, _TConListDescr>) = _Ident1
[auth2 ] author-id(<_Ident1, _Ident2, _ColListDescr, _TConListDescr>) = _Ident1

[tid1  ] table-id(<_Ident1, _Ident2, _ColListDescr, _TConListDescr>) = _Ident2
[tid2  ] table-id(<_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) = _Ident2

[tocc1 ] t-occurs(_Ident, []) = false
[tocc2 ] t-occurs(_Ident, [_TVDescr _TVDescr*]) = true
         when _Ident = table-id(_TVDescr)
[tocc3 ] t-occurs(_Ident, [_TVDescr _TVDescr*]) =
         t-occurs(_Ident, [_TVDescr*])
         when _Ident != table-id(_TVDescr)

[tv1   ] tv-check(_EnvDescr, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
         coll-check(_ColListDescr)
[tv2   ] tv-check(_EnvDescr, <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
         _Error
```

```
          when query-check(_EnvDescr, _QuerySpec) = <_Error, _Ident, _ColListDescr>,
               _Error != OK
 [tv3    ] tv-check(_EnvDescr, <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
          vcoll-check(_IdentList, _ColListDescr)
          when query-check(_EnvDescr, _QuerySpec) = <OK, _Ident, _ColListDescr>

 [coll1 ] coll-check([]) = OK
 [coll2 ] coll-check([_ColDescr*1 _ColDescr _ColDescr*2]) =
          Column Name column-id(_ColDescr) should be unique!
          when c-occurs(column-id(_ColDescr), [_ColDescr*1 _ColDescr*2]) = true
 [coll3 ] coll-check([_ColDescr*1 _ColDescr _ColDescr*2]) =
          coll-check([_ColDescr*1 _ColDescr*2])
          when c-occurs(column-id(_ColDescr), [_ColDescr*1 _ColDescr*2]) = false

 [cid1  ] column-id(<_Ident, _DTDescr, _Literal, _CConListDescr, _Bool>) = _Ident

 [cocc1 ] c-occurs(_Ident, []) = false
 [cocc2 ] c-occurs(_Ident, [_ColDescr _ColDescr*]) = true
          when _Ident = column-id(_ColDescr)
 [cocc3 ] c-occurs(_Ident, [_ColDescr _ColDescr*]) =
          c-occurs(_Ident, [_ColDescr*])
          when _Ident != column-id(_ColDescr)

 [vcoll1] vcoll-check(_IdentList, _ColListDescr) =
          should-provide-viewcolumnlist(_IdentList, _ColListDescr) AND THEN
          all-ids-must-be-different(_IdentList) AND THEN
          right-number-of-viewcolumns(_IdentList, _ColListDescr)

 [prov2 ] should-provide-viewcolumnlist([_Ident _Ident*], _ColListDescr) = OK
 [prov3 ] should-provide-viewcolumnlist([], []) = OK
 [prov4 ] should-provide-viewcolumnlist([], [_ColDescr _ColDescr*]) =
          should-provide-viewcolumnlist([], [_ColDescr*])
          when _ColDescr = <_Ident, _DTDescr, _DefDescr, _CConListDescr, _Bool>,
               _Ident != _
 [prov5 ] should-provide-viewcolumnlist([], [_ColDescr _ColDescr*]) =
          Should provide viewcolumnlist!
          when _ColDescr = <_Ident, _DTDescr, _DefDescr, _CConListDescr, _Bool>,
               _Ident = _
 [prov6 ] should-provide-viewcolumnlist([], [_ColDescr _ColDescr*]) =
          Should provide viewcolumnlist!
          when _ColDescr = <_Ident, _DTDescr, _DefDescr, _CConListDescr, _Bool>,
               _Ident != _,
               c-occurs(_Ident, [_ColDescr*]) = true

 [diff1 ] all-ids-must-be-different([]) = OK
 [diff2 ] all-ids-must-be-different([_Ident*1 _Ident _Ident*2]) =
          all-ids-must-be-different([_Ident*1 _Ident*2])
          when i-occurs(_Ident, [_Ident*1 _Ident*2]) = false
 [diff3 ] all-ids-must-be-different([_Ident*1 _Ident _Ident*2]) =
          All viewcolumns must be different!
          when i-occurs(_Ident, [_Ident*1 _Ident*2]) = true

 [iocc1 ] i-occurs(_Ident, []) = false
 [iocc2 ] i-occurs(_Ident, [_Ident _Ident*]) = true
 [iocc3 ] i-occurs(_Ident, [_Ident' _Ident*]) =
          i-occurs(_Ident, [_Ident*])
          when _Ident != _Ident'

 [numb1 ] right-number-of-viewcolumns([], []) = OK
 [numb2 ] right-number-of-viewcolumns([_Ident _Ident*], []) =
          Too many viewcolumns specified!
 [numb3 ] right-number-of-viewcolumns([], [_ColDescr _ColDescr*]) =
          Not enough viewcolumns specified!
 [numb4 ] right-number-of-viewcolumns([_Ident _Ident*], [_ColDescr _ColDescr*]) =
          right-number-of-viewcolumns([_Ident*], [_ColDescr*])

 [expe1 ] expand-env(_EnvDescr, <_Ident, []>) = <_Ident, []>
 [expe2 ] expand-env(_EnvDescr, <_Ident, [_SDescr _SDescr*]>) =
          <_Ident', [_SDescr' _SDescr*']>
          when expand-sch(_EnvDescr, _SDescr) = _SDescr',
               expand-env(_EnvDescr, <_Ident, [_SDescr*]>) = <_Ident', [_SDescr*']>

 [exps1 ] expand-sch(_EnvDescr, <_Ident, [], _PListDescr>) = <_Ident, [], _PListDescr>
 [exps2 ] expand-sch(_EnvDescr, <_Ident, [_TVDescr _TVDescr*], _PListDescr>) =
          <_Ident', [_TVDescr' _TVDescr*'], _PListDescr'>
          when expand-tv(_EnvDescr, _TVDescr) = _TVDescr',
               expand-sch(_EnvDescr, <_Ident, [_TVDescr*], _PListDescr>) = <_Ident', [_TVDescr*'], _PListDescr'>

 [exptv1] expand-tv(_EnvDescr, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
          <_Ident1, _Ident2, _ColListDescr, _TConListDescr>
 [exptv2] expand-tv(_EnvDescr, <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
          <_Ident1, _Ident2, rename(_IdentList, _ColListDescr), []>
          when query-check(_EnvDescr, _QuerySpec) = <OK, _Ident, _ColListDescr>

 [ren1  ] rename([], []) = []
 [ren2  ] rename([_Ident _Ident*],
                 [<_Ident', _DTDescr, _DefDescr, _CConListDescr, _Bool> _ColDescr*]) =
          [<_Ident, _DTDescr, _DefDescr, _CConListDescr, _Bool> _ColDescr*']
          when rename([_Ident*], [_ColDescr*]) = [_ColDescr*']
end SchemaCheck
```

```
module TC_ValueExpr

imports
  Errors
  SchemaDescr
  ValueExpressions

exports
  sorts
    VE_EDP %% _EDP = Error Description Pair
  context-free syntax
    "<" ERROR "," DTDescr ">"                                  -> VE_EDP
    "Column" ColumnSpec "undefined!"                           -> ERROR
    "Column" ColumnSpec "ambiguous!"                           -> ERROR
    "Type of operand(s) of" StringLit "may not be string!" -> ERROR
    "Type of func-arg" ValueExpr "may not be string!"      -> ERROR
    "Parameters not implemented!"                              -> ERROR
    "Variables not implemented!"                               -> ERROR
    ve-check  "(" TVListDescr "," ValueExpr ")"                -> VE_EDP

hiddens
  context-free syntax
    c-check   "(" TVListDescr "," ColumnSpec ")"               -> VE_EDP
    exp-check "(" StringLit "," VE_EDP "," VE_EDP ")"      -> VE_EDP
    exp-type  "(" TypDescr "," TypDescr ")"                    -> TypDescr
    exp-prec  "(" INT "," INT ")"                              -> INT
    exp-scale "(" StringLit "," INT "," INT ")"                -> INT
    length    "(" StringLit ")"                                -> INT
    length    "(" Unsigned ")"                                 -> INT
    precision "(" ExactLit ")"                                 -> INT
    scale     "(" ExactLit ")"                                 -> INT
    precision "(" ApproxLit ")"                                -> INT

equations
[ve1   ] ve-check(_TVListDescr, _ValueExpr + _Term) =
         exp-check('+', ve-check(_TVListDescr, _ValueExpr), ve-check(_TVListDescr, _Term))
[ve2   ] ve-check(_TVListDescr, _ValueExpr - _Term) =
         exp-check('-', ve-check(_TVListDescr, _ValueExpr), ve-check(_TVListDescr, _Term))
[ve3   ] ve-check(_TVListDescr, _Term * _Factor) =
         exp-check('*', ve-check(_TVListDescr, _Term), ve-check(_TVListDescr, _Factor))
[ve4   ] ve-check(_TVListDescr, _Term / _Factor) =
         exp-check('/', ve-check(_TVListDescr, _Term), ve-check(_TVListDescr, _Factor))
[ve5   ] ve-check(_TVListDescr, + _Primary) =
         exp-check('+', ve-check(_TVListDescr, _Primary), ve-check(_TVListDescr, _Primary))
[ve6   ] ve-check(_TVListDescr, - _Primary) =
         exp-check('-', ve-check(_TVListDescr, _Primary), ve-check(_TVListDescr, _Primary))
[ve7   ] ve-check(_TVListDescr, _ParameterName INDICATOR _ParameterName') =
         <Parameters not implemented!, <Notype,0,0>>
         %% case _ParameterName: see case _ColumnSpec
[ve8   ] ve-check(_TVListDescr, _EmbeddedVarName INDICATOR _EmbeddedVarName') =
         <Variables not implemented!, <Notype,0,0>>
[ve9   ] ve-check(_TVListDescr, _EmbeddedVarName) =
         <Variables not implemented!, <Notype,0,0>>
[ve10  ] ve-check(_TVListDescr, _StringLit) =
         <OK, <String, length(_StringLit), 0>>
[ve11  ] ve-check(_TVListDescr, _ExactLit) =
         <OK, <Exact, precision(_ExactLit), scale(_ExactLit)>>
[ve12  ] ve-check(_TVListDescr, _ApproxLit) =
         <OK, <Approx, precision(_ApproxLit), 0>>
[ve13  ] ve-check(_TVListDescr, USER) =
         <OK, <String, 18, 0>> %% length is impl.defined; 18 = max length of ident
[ve13  ] ve-check(_TVListDescr, _ColumnSpec) =
         c-check(_TVListDescr, _ColumnSpec)
[ve14  ] ve-check(_TVListDescr, (_ValueExpr)) =
         ve-check(_TVListDescr, _ValueExpr)
[ve15  ] ve-check(_TVListDescr, COUNT(*)) =
         <OK, <Exact, 1113, 0>> %% precision impl-def
[ve16  ] ve-check(_TVListDescr, COUNT(DISTINCT _ColumnSpec)) =
         <OK, <Exact, 1113, 0>> %% precision impl-def
         when c-check(_TVListDescr, _ColumnSpec) = <OK, _DTDescr>
[ve17  ] ve-check(_TVListDescr, COUNT(DISTINCT _ColumnSpec)) =
         <_Error, <Notype,0,0>>
         when c-check(_TVListDescr, _ColumnSpec) = <_Error, _DTDescr>,
              _Error != OK
[ve18  ] ve-check(_TVListDescr, MAX(DISTINCT _ColumnSpec)) =
         c-check(_TVListDescr, _ColumnSpec)
[ve19  ] ve-check(_TVListDescr, MIN(DISTINCT _ColumnSpec)) =
         c-check(_TVListDescr, _ColumnSpec)
[ve20  ] ve-check(_TVListDescr, MAX(ALL _ValueExpr)) =
         ve-check(_TVListDescr, _ValueExpr)
[ve21  ] ve-check(_TVListDescr, MIN(ALL _ValueExpr)) =
         ve-check(_TVListDescr, _ValueExpr)
[ve22  ] ve-check(_TVListDescr, MAX(_ValueExpr)) =
         ve-check(_TVListDescr, _ValueExpr)
[ve23  ] ve-check(_TVListDescr, MIN(_ValueExpr)) =
         ve-check(_TVListDescr, _ValueExpr)
[ve24  ] ve-check(_TVListDescr, AVG(DISTINCT _ColumnSpec)) =
         ve-check(_TVListDescr, AVG(_ColumnSpec))
         %% note: a ColumnSpec IS a ValueExpr!
[ve25  ] ve-check(_TVListDescr, AVG(ALL _ValueExpr)) =
```

```
          ve-check(_TVListDescr, AVG(_ValueExpr))
 [ve26  ] ve-check(_TVListDescr, AVG(_ValueExpr)) =
          <OK, <_TypDescr, _Int1, _Int2>>
          when ve-check(_TVListDescr, _ValueExpr) = <OK, _DTDescr>,
               _DTDescr = <_TypDescr, _Int1, _Int2>,
               _TypDescr != String
 [ve27  ] ve-check(_TVListDescr, AVG(_ValueExpr)) =
          <Type of func-arg _ValueExpr may not be string!, <Notype,0,0>>
          when ve-check(_TVListDescr, _ValueExpr) = <OK, _DTDescr>,
               _DTDescr = <String, _Int1, _Int2>
 [ve28  ] ve-check(_TVListDescr, AVG(_ValueExpr)) =
          <_Error, <Notype,0,0>>
          when ve-check(_TVListDescr, _ValueExpr) = <_Error; _DTDescr>,
               _Error != OK
 [ve29  ] ve-check(_TVListDescr, SUM(DISTINCT _ColumnSpec)) =
          ve-check(_TVListDescr, SUM(_ColumnSpec))
          %% a ColumnSpec IS a ValueExpr!
 [ve30  ] ve-check(_TVListDescr, SUM(ALL _ValueExpr)) =
          ve-check(_TVListDescr, SUM(_ValueExpr))
 [ve31  ] ve-check(_TVListDescr, SUM(_ValueExpr)) =
          ve-check(_TVListDescr, AVG(_ValueExpr))

 [c1    ] c-check(_TVListDescr, _ColumnSpec) =
          <OK, _DTDescr>
          when lookup-column(_ColumnSpec, _TVListDescr) = [_ColDescr],
               _ColDescr = <_Ident, _DTDescr, _Literal, _CConListDescr, _Bool>
 [c2    ] c-check(_TVListDescr, _ColumnSpec) =
          <Column _ColumnSpec undefined!, <Notype,0,0>>
          when lookup-column(_ColumnSpec, _TVListDescr) = []
 [c3    ] c-check(_TVListDescr, _ColumnSpec) =
          <Column _ColumnSpec ambiguous!, <Notype,0,0>>
          when lookup-column(_ColumnSpec, _TVListDescr) = [_ColDescr _ColDescr+]

 [exp1  ] exp-check(_StringLit, <_Error1, _DTDescr1>, <_Error2, _DTDescr2>) =
          <_Error1 AND _Error2, <Notype,0,0>>
          when _Error1 AND _Error2 != OK
 [exp2  ] exp-check(_StringLit, <_Error1, _DTDescr1>, <_Error2, _DTDescr2>) =
          <Type of operand(s) of _StringLit may not be string!, <Notype,0,0>>
          when _Error1 = OK, _Error2 = OK,
               _DTDescr1 = <String, _Int1, _Int2>
 [exp3  ] exp-check(_StringLit, <_Error1, _DTDescr1>, <_Error2, _DTDescr2>) =
          <Type of operand(s) of _StringLit may not be string!, <Notype,0,0>>
          when _Error1 = OK, _Error2 = OK,
               _DTDescr2 = <String, _Int1, _Int2>
 [exp4  ] exp-check(_StringLit, <_Error1, _DTDescr1>, <_Error2, _DTDescr2>) =
          <OK, <exp-type(_TypDescr1, _TypDescr2),
                exp-prec(_Int1, _Int2),
                exp-scale(_StringLit, _Int1', _Int2')>>
          when _Error1 = OK, _Error2 = OK,
               _DTDescr1 = <_TypDescr1, _Int1, _Int1'>, _TypDescr1 != String,
               _DTDescr2 = <_TypDescr2, _Int2, _Int2'>, _TypDescr2 != String

[etyp1 ] exp-type(Exact,  Exact)  = Exact
[etyp2 ] exp-type(Exact,  Approx) = Approx
[etyp3 ] exp-type(Approx, Exact)  = Approx
[etyp4 ] exp-type(Approx, Approx) = Approx

[epr1  ] exp-prec(_Int1, _Int2) = max(_Int1, _Int2) %% implementor-defined

[esc1  ] exp-scale('+', _Int1, _Int2) = max(_Int1, _Int2) %% eig alleen voor exact
[esc2  ] exp-scale('-', _Int1, _Int2) = max(_Int1, _Int2) %% eig alleen voor exact
[esc3  ] exp-scale('*', _Int1, _Int2) = _Int1 + _Int2 %% eig alleen voor exact
[esc4  ] exp-scale('/', _Int1, _Int2) = _Int1 + _Int2 %% eig alleen voor exact

[len1  ] length(stringlit("'" _Char "'")) = 1
[len2  ] length(stringlit("'" _Char _Char+ "'")) =
         inc(length(stringlit("'" _Char+ "'")))
[len3  ] length(unsigned(_Char)) = 1
[len4  ] length(unsigned(_Char _Char+)) =
         inc(length(unsigned(_Char+)))

[prec1 ] precision(exactlit("+" _Char+)) =
         precision(exactlit(_Char+))
[prec2 ] precision(exactlit("-" _Char+)) =
         precision(exactlit(_Char+))
[prec3 ] precision(exactlit(_Char*1 "." _Char*2)) =
         length(stringlit("'" _Char*1 "'")) +
         length(stringlit("'" _Char*2 "'"))
%% case exactlit w/o/ "." not yet done!
[prec4 ] precision(approxlit(_Char+1 "E" _Char+2)) =
         precision(exactlit(_Char+1))

[scale1] scale(exactlit("+" _Char+)) =
         scale(exactlit(_Char+))
[scale2] scale(exactlit("-" _Char+)) =
         scale(exactlit(_Char+))
[scale3] scale(exactlit(_Char*1 "." _Char*2)) =
         length(stringlit("'" _Char*1 "'"))
%% case exactlit w/o/ "." not yet done!
end TC_ValueExpr
```

```
module TC_QueryPred_syn

imports

  Errors
  Predicates
  SchemaDescr
  QuerySpecs
  TC_ValueExpr

exports

  sorts

    QUERY_EDP       %% _EDP = Error Description Pair
    SELL_EDP
    TEXPR_EDP
    FROM_EDP
    WHERE_EDP
    GROUP_EDP
    HAVING_EDP
    SEARCH_EDP
    TABLE_EDP

  context-free syntax

    "<" ERROR "," Ident "," ColListDescr ">"          -> QUERY_EDP
    "<" ERROR "," ColListDescr ">"                    -> SELL_EDP
    "<" ERROR "," TVListDescr ">"                     -> TEXPR_EDP
    "<" ERROR "," TVListDescr ">"                     -> FROM_EDP
    "<" ERROR "," ">"                                 -> WHERE_EDP
    "<" ERROR "," ">"                                 -> GROUP_EDP
    "<" ERROR "," ">"                                 -> HAVING_EDP
    "<" ERROR "," ">"                                 -> SEARCH_EDP
    "<" ERROR "," Ident "," TVDescr ">"               -> TABLE_EDP

    "Table Ref" TableName "undefined!"                   -> ERROR
    "Table Ref" TableName "ambiguous!"                   -> ERROR

    query-check  "(" EnvDescr "," QuerySpec ")"                          -> QUERY_EDP
    sell-check   "(" EnvDescr "," TVListDescr "," SelectList ")"         -> SELL_EDP
    texpr-check  "(" EnvDescr "," TVListDescr "," TableExpr ")"          -> TEXPR_EDP
    from-check   "(" EnvDescr "," FromClause ")"                         -> FROM_EDP
    where-check  "(" EnvDescr "," TVListDescr "," WhereClause ")"        -> WHERE_EDP
    group-check  "(" TVListDescr "," GroupByClause ")"                   -> GROUP_EDP
    having-check "(" EnvDescr "," TVListDescr "," HavingClause ")"       -> HAVING_EDP
    search-check "(" EnvDescr "," TVListDescr "," SearchCondition ")"    -> SEARCH_EDP
    table-check  "(" EnvDescr "," TableReference ")"                     -> TABLE_EDP
    pred-check   "(" EnvDescr "," TVListDescr "," Predicate ")"          -> ERROR
    subq-check   "(" EnvDescr "," TVListDescr "," SubQuery ")"           -> QUERY_EDP
    subval-check "(" EnvDescr "," TVListDescr "," SubQuery ")"           -> VE_EDP
    column-check "(" ColListDescr ")"                                    -> VE_EDP

    comparable  "(" VE_EDP "," VE_EDP ")"                    -> ERROR
    comparable  "(" DTDescr "," DTDescr ")"                  -> BOOL

  variables

    "_QUERY_EDP"                -> QUERY_EDP
    "_SELL_EDP"                 -> SELL_EDP
    "_TEXPR_EDP"                -> TEXPR_EDP
    "_FROM_EDP"                 -> FROM_EDP

end TC_QueryPred_syn
```

```
module TC_Pred_sem

imports

  TC_QueryPred_syn

exports

  context-free syntax

    "SubQuery must result in a single column!"                  -> ERROR
    "Types are not comparable!"                                 -> ERROR
    "Type of" ValueExpr "must be a string!"                     -> ERROR
    "Value" ValueExpr "must be a single char!"                  -> ERROR

hiddens

  context-free syntax

    must-be-string "(" TVListDescr "," ValueExpr ")"            -> ERROR
    must-be-length1 "(" TVListDescr "," ValueExpr ")"           -> ERROR

equations

[pred1 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr1 _CompOp _ValueExpr2) =
         comparable(ve-check(_TVListDescr, _ValueExpr1), ve-check(_TVListDescr, _ValueExpr2))
[pred2 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr _CompOp _SubQuery) =
         comparable(ve-check(_TVListDescr, _ValueExpr), subval-check(_EnvDescr, _TVListDescr, _SubQuery))
[pred3 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr1 NOT BETWEEN _ValueExpr2 AND _ValueExpr3) =
         comparable(ve-check(_TVListDescr, _ValueExpr1), ve-check(_TVListDescr, _ValueExpr2)) AND
         comparable(ve-check(_TVListDescr, _ValueExpr1), ve-check(_TVListDescr, _ValueExpr3))
[pred4 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr1 BETWEEN _ValueExpr2 AND _ValueExpr3) =
         comparable(ve-check(_TVListDescr, _ValueExpr1), ve-check(_TVListDescr, _ValueExpr2)) AND
         comparable(ve-check(_TVListDescr, _ValueExpr1), ve-check(_TVListDescr, _ValueExpr3))
[pred5 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr IN _SubQuery) =
         comparable(ve-check(_TVListDescr, _ValueExpr), subval-check(_EnvDescr, _TVListDescr, _SubQuery))
[pred6 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr IN _ValueSpec) =
         comparable(ve-check(_TVListDescr, _ValueExpr), ve-check(_TVListDescr, _ValueSpec))
[pred7 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr IN _ValueSpec, _ValueSpec+) =
         comparable(ve-check(_TVListDescr, _ValueExpr), ve-check(_TVListDescr, _ValueSpec)) AND THEN
         pred-check(_EnvDescr, _TVListDescr, _ValueExpr NOT IN _ValueSpec+)
[pred8 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr NOT IN _SubQuery) =
         pred-check(_EnvDescr, _TVListDescr, _ValueExpr     IN _SubQuery)
[pred9 ] pred-check(_EnvDescr, _TVListDescr, _ValueExpr NOT IN _InValueList) =
         pred-check(_EnvDescr, _TVListDescr, _ValueExpr     IN _InValueList)
[pred10] pred-check(_EnvDescr, _TVListDescr, _ColumnSpec LIKE _ValueSpec1 ESCAPE _ValueSpec2) =
         must-be-string(_TVListDescr, _ColumnSpec) AND
         must-be-string(_TVListDescr, _ValueSpec1) AND
         (must-be-string(_TVListDescr, _ValueSpec2) AND THEN
          must-be-length1(_TVListDescr, _ValueSpec2))
[pred11] pred-check(_EnvDescr, _TVListDescr, _ColumnSpec LIKE _ValueSpec) =
         must-be-string(_TVListDescr, _ColumnSpec) AND
         must-be-string(_TVListDescr, _ValueSpec)
[pred12] pred-check(_EnvDescr, _TVListDescr, _ColumnSpec NOT LIKE _ValueSpec1 ESCAPE _ValueSpec2) =
         pred-check(_EnvDescr, _TVListDescr, _ColumnSpec     LIKE _ValueSpec1 ESCAPE _ValueSpec2)
[pred13] pred-check(_EnvDescr, _TVListDescr, _ColumnSpec NOT LIKE _ValueSpec) =
         pred-check(_EnvDescr, _TVListDescr, _ColumnSpec     LIKE _ValueSpec)
[pred14] pred-check(_EnvDescr, _TVListDescr, _ColumnSpec IS NULL) =
         _Error
         when ve-check(_TVListDescr, _ColumnSpec) = <_Error, _DTDescr>
[pred15] pred-check(_EnvDescr, _TVListDescr, _ColumnSpec IS NOT NULL) =
         pred-check(_EnvDescr, _TVListDescr, _ColumnSpec IS     NULL)
[pred16] pred-check(_EnvDescr, _TVListDescr, _ValueExpr _CompOp _Quantifier _SubQuery) =
         comparable(ve-check(_TVListDescr, _ValueExpr), subval-check(_EnvDescr, _TVListDescr, _SubQuery))
[pred17] pred-check(_EnvDescr, _TVListDescr, EXISTS _SubQuery) =
         _Error
         when subq-check(_EnvDescr, _TVListDescr, _SubQuery) = <_Error, _Ident, _ColListDescr>

[sqve1 ] subval-check(_EnvDescr, _TVListDescr, _SubQuery) =
         <_Error, <Notype,0,0>>
         when subq-check(_EnvDescr, _TVListDescr, _SubQuery) = <_Error, _Ident, _ColListDescr>,
              _Error != OK
[sqve2 ] subval-check(_EnvDescr, _TVListDescr, _SubQuery) =
         <_Error, _DTDescr>
         when subq-check(_EnvDescr, _TVListDescr, _SubQuery) = <OK, _Ident, _ColListDescr>,
              column-check(_ColListDescr) = <_Error, _DTDescr>

[col1  ] column-check([]) = <ERROR!, <Notype,0,0>> %% something went wrong!
[col2  ] column-check([_ColDescr _ColDescr+]) =
         <SubQuery must result in a single column!, <Notype,0,0>>
[col3  ] column-check([<_Ident, _DTDescr, _DefDescr, _CConListDescr, _Bool>]) =
         <OK, _DTDescr>

[comp1 ] comparable(<_Error1, _DTDescr1>, <_Error2, _DTDescr2>) =
         _Error1 AND _Error2
         when _Error1 AND _Error2 != OK
[comp2 ] comparable(<OK, _DTDescr1>, <OK, _DTDescr2>) =
         Types are not comparable!
         when comparable(_DTDescr1, _DTDescr2) != true  %% cave: niet test op false!
[comp3 ] comparable(<OK, _DTDescr1>, <OK, _DTDescr2>) =
```

```
          OK
          when comparable(_DTDescr1, _DTDescr2) = true

[comp4 ] comparable(<String, _Int1, _Int2>, <String, _Int1', _Int2'>) = true
[comp5 ] comparable(<Exact,  _Int1, _Int2>, <Exact,  _Int1', _Int2'>) = true
[comp6 ] comparable(<Approx, _Int1, _Int2>, <Approx, _Int1', _Int2'>) = true
[comp7 ] comparable(<Approx, _Int1, _Int2>, <Exact,  _Int1', _Int2'>) = true
[comp8 ] comparable(<Exact,  _Int1, _Int2>, <Approx, _Int1', _Int2'>) = true
%% rest niet specificeren => alle andere combinaties leveren != true (en niet false)

[mbstr1] must-be-string(_TVListDescr, _ValueExpr) =
          OK
          when ve-check(_TVListDescr, _ValueExpr) = <OK, <String, _Int1, _Int2>>
[mbstr2] must-be-string(_TVListDescr, _ValueExpr) =
          Type of _ValueExpr must be a string!
          when ve-check(_TVListDescr, _ValueExpr) = <OK, <_TypDescr, _Int1, _Int2>>,
               _TypDescr != String
[mbstr3] must-be-string(_TVListDescr, _ValueExpr) =
          _Error
          when ve-check(_TVListDescr, _ValueExpr) = <_Error, _DTDescr>,
               _Error != OK

[mbl11 ] must-be-length1(_TVListDescr, _ValueExpr) =
          OK
          when ve-check(_TVListDescr, _ValueExpr) = <OK, <_TypDescr, _Int1, _Int2>>,
               _Int1 = 1
[mbl12 ] must-be-length1(_TVListDescr, _ValueExpr) =
          Value _ValueExpr must be a single char!
          when ve-check(_TVListDescr, _ValueExpr) = <OK, <_TypDescr, _Int1, _Int2>>,
               _Int1 != 1

end TC_Pred_sem
```

```
module TC_Query_sem

imports

  TC_QueryPred_syn

exports

  context-free syntax

    "Table Ref" TableName "exposed ambiguous!"          -> ERROR

hiddens

  context-free syntax

    get-column-descrs "(" EnvDescr "," TVListDescr ")"  -> ColListDescr
    get-column-descrs "(" EnvDescr "," TVDescr ")"      -> ColListDescr

    overlay-columns   "(" IdentList "," ColListDescr")" -> ColListDescr

    t-occurs  "(" Ident "," TVListDescr ")"             -> BOOL
    table-id  "(" TVDescr ")"                           -> Ident

equations

[query1] query-check(_EnvDescr, SELECT ALL _SelectList _TableExpr) =
         <_Error1 AND THEN _Error2, A, _ColListDescr>
         when texpr-check(_EnvDescr, [], _TableExpr)  = <_Error1, _TVListDescr>,
              sell-check(_EnvDescr, _TVListDescr, _SelectList) = <_Error2, _ColListDescr>
[query2] query-check(_EnvDescr, SELECT DISTINCT _SelectList _TableExpr) =
         <_Error1 AND THEN _Error2, D, _ColListDescr>
         when texpr-check(_EnvDescr, [], _TableExpr)  = <_Error1, _TVListDescr>,
              sell-check(_EnvDescr, _TVListDescr, _SelectList) = <_Error2, _ColListDescr>
[query3] query-check(_EnvDescr, SELECT _SelectList _TableExpr) =
         <_Error1 AND THEN _Error2, X, _ColListDescr>
         when texpr-check(_EnvDescr, [], _TableExpr)  = <_Error1, _TVListDescr>,
              sell-check(_EnvDescr, _TVListDescr, _SelectList) = <_Error2, _ColListDescr>

[texpr1] texpr-check(_EnvDescr, _TVListDescr, _FromClause _WhereClause _GroupByClause _HavingClause) =
         <_Error1 AND THEN _Error2 AND THEN _Error3 AND THEN _Error4, _TVListDescr'>
         when from-check(_EnvDescr, _FromClause) = <_Error1, _TVListDescr'>,
              combine-tables(_TVListDescr', _TVListDescr) = _TVListDescr'',
              where-check(_EnvDescr, _TVListDescr'', _WhereClause) = <_Error2, >,
              group-check(_TVListDescr', _GroupByClause) = <_Error3, >,
              having-check(_EnvDescr, _TVListDescr'', _HavingClause) = <_Error4, >

[texpr2] texpr-check(_EnvDescr, _TVListDescr, _FromClause _WhereClause _GroupByClause) =
         <_Error1 AND THEN _Error2 AND THEN _Error3, _TVListDescr'>
         when from-check(_EnvDescr, _FromClause) = <_Error1, _TVListDescr'>,
              combine-tables(_TVListDescr', _TVListDescr) = _TVListDescr'',
              where-check(_EnvDescr, _TVListDescr'', _WhereClause) = <_Error2, >,
              group-check(_TVListDescr', _GroupByClause) = <_Error3, >

[texpr3] texpr-check(_EnvDescr, _TVListDescr, _FromClause _WhereClause _HavingClause) =
         <_Error1 AND THEN _Error2 AND THEN _Error3, _TVListDescr'>
         when from-check(_EnvDescr, _FromClause) = <_Error1, _TVListDescr'>,
              combine-tables(_TVListDescr', _TVListDescr) = _TVListDescr'',
              where-check(_EnvDescr, _TVListDescr'', _WhereClause) = <_Error2, >,
              having-check(_EnvDescr, _TVListDescr'', _HavingClause) = <_Error3, >

[texpr4] texpr-check(_EnvDescr, _TVListDescr, _FromClause _WhereClause) =
         <_Error1 AND THEN _Error2, _TVListDescr'>
         when from-check(_EnvDescr, _FromClause) = <_Error1, _TVListDescr'>,
              combine-tables(_TVListDescr', _TVListDescr) = _TVListDescr'',
              where-check(_EnvDescr, _TVListDescr'', _WhereClause) = <_Error2, >

[texpr5] texpr-check(_EnvDescr, _TVListDescr, _FromClause _GroupByClause _HavingClause) =
         <_Error1 AND THEN _Error2 AND THEN _Error3, _TVListDescr'>
         when from-check(_EnvDescr, _FromClause) = <_Error1, _TVListDescr'>,
              combine-tables(_TVListDescr', _TVListDescr) = _TVListDescr'',
              group-check(_TVListDescr', _GroupByClause) = <_Error2, >,
              having-check(_EnvDescr, _TVListDescr'', _HavingClause) = <_Error3, >

[texpr6] texpr-check(_EnvDescr, _TVListDescr, _FromClause _GroupByClause) =
         <_Error1 AND THEN _Error2, _TVListDescr'>
         when from-check(_EnvDescr, _FromClause) = <_Error1, _TVListDescr'>,
              combine-tables(_TVListDescr', _TVListDescr) = _TVListDescr'',
              group-check(_TVListDescr', _GroupByClause) = <_Error2, >

[texpr7] texpr-check(_EnvDescr, _TVListDescr, _FromClause _HavingClause) =
         <_Error1 AND THEN _Error2, _TVListDescr'>
         when from-check(_EnvDescr, _FromClause) = <_Error1, _TVListDescr'>,
              combine-tables(_TVListDescr', _TVListDescr) = _TVListDescr'',
              having-check(_EnvDescr, _TVListDescr'', _HavingClause) = <_Error2, >

[texpr8] texpr-check(_EnvDescr, _TVListDescr, _FromClause) =
         <_Error, _TVListDescr'>
         when from-check(_EnvDescr, _FromClause) = <_Error, _TVListDescr'>
```

```
[from1 ] from-check(_EnvDescr, FROM _TableRef) =
         <_Error, [_TVDescr]>
         when table-check(_EnvDescr, _TableRef) = <_Error, _Ident, _TVDescr>
[from2] from-check(_EnvDescr, FROM _TableRef, _TableRef+) =
         <_Error1 AND _Error2, [_TVDescr _TVDescr*]>
         when table-check(_EnvDescr, _TableRef) = <_Error1, _Ident, _TVDescr>,
              from-check(_EnvDescr, FROM _TableRef+) = <_Error2, [_TVDescr*]>,
              t-occurs(_Ident, [_TVDescr*]) != true
[from3] from-check(_EnvDescr, FROM _TableRef, _TableRef+) =
         <Table Ref _Ident exposed ambiguous!, [_TVDescr _TVDescr*]>
         when table-check(_EnvDescr, _TableRef) = <_Error1, _Ident, _TVDescr>,
              from-check(_EnvDescr, FROM _TableRef+) = <_Error2, [_TVDescr*]>,
              t-occurs(_Ident, [_TVDescr*]) = true

[tocc1 ] t-occurs(_Ident, []) = false
[tocc2 ] t-occurs(_Ident, [_TVDescr _TVDescr*]) = true
         when _Ident = table-id(_TVDescr)
[tocc3 ] t-occurs(_Ident, [_TVDescr _TVDescr*]) =
         t-occurs(_Ident, [_TVDescr*])
         when _Ident != table-id(_TVDescr)

[tid1  ] table-id(<_Ident1, _Ident2, _ColListDescr, _TConListDescr>) = _Ident2
[tid2  ] table-id(<_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) = _Ident2

[table1] table-check(_EnvDescr, _Ident1._Ident2) =
         <OK, _Ident2, _TVDescr>
         when lookup-table(_Ident1._Ident2, _EnvDescr) = [_TVDescr]
[table2] table-check(_EnvDescr, _Ident2) =
         <OK, _Ident2, _TVDescr>
         when lookup-table(_Ident2, _EnvDescr) = [_TVDescr]
 table3] table-check(_EnvDescr, _Ident1._Ident2 _Ident3) =
         <OK, _Ident3, correname(_Ident3, _TVDescr)>
         when lookup-table(_Ident2, _EnvDescr) = [_TVDescr]
[table4] table-check(_EnvDescr, _Ident2 _Ident3) =
         <OK, _Ident3, correname(_Ident3, _TVDescr)>
         when lookup-table(_Ident2, _EnvDescr) = [_TVDescr]
[table5] table-check(_EnvDescr, _TableName) =
         <Table Ref _TableName undefined!, _, <_, _, [], []>>
         when lookup-table(_TableName, _EnvDescr) = []
[table6] table-check(_EnvDescr, _TableName _CorrelationName) =
         <Table Ref _TableName undefined!, _, <_, _, [], []>>
         when lookup-table(_TableName, _EnvDescr) = []
[table7] table-check(_EnvDescr, _TableName) =
         <Table Ref _TableName ambiguous!, _, _TVDescr>
         when lookup-table(_TableName, _EnvDescr) = [_TVDescr _TVDescr+]
[table8] table-check(_EnvDescr, _TableName _CorrelationName) =
         <Table Ref _TableName ambiguous!, _, _TVDescr>
         when lookup-table(_TableName, _EnvDescr) = [_TVDescr _TVDescr+]

[where1] where-check(_EnvDescr, _TVListDescr, WHERE _SearchCondition) =
         <_Error, >
         when search-check(_EnvDescr, _TVListDescr, _SearchCondition) = <_Error, >

[group1] group-check(_TVListDescr, GROUP BY _ColumnSpec) =
         <_Error, >
         when ve-check(_TVListDescr, _ColumnSpec) = <_Error, _DTDescr>
[group2] group-check(_TVListDescr, GROUP BY _ColumnSpec, _ColumnSpec+) =
         <_Error1 AND _Error2, >
         when ve-check(_TVListDescr, _ColumnSpec) = <_Error1, _DTDescr>,
              group-check(_TVListDescr, GROUP BY _ColumnSpec+) = <_Error2, >

[havng1] having-check(_EnvDescr, _TVListDescr, HAVING _SearchCondition) =
         <_Error, >
         when search-check(_EnvDescr, _TVListDescr, _SearchCondition) = <_Error, >

[surch1] search-check(_EnvDescr, _TVListDescr, _SearchCondition OR _BooleanTerm) =
         <_Error1 AND _Error2, >
         when search-check(_EnvDescr, _TVListDescr, _SearchCondition) = <_Error1, >,
              search-check(_EnvDescr, _TVListDescr, _BooleanTerm) = <_Error2, >
[surch2] search-check(_EnvDescr, _TVListDescr, _BooleanTerm AND _BooleanFactor) =
         <_Error1 AND _Error2, >
         when search-check(_EnvDescr, _TVListDescr, _BooleanTerm) = <_Error1, >,
              search-check(_EnvDescr, _TVListDescr, _BooleanFactor) = <_Error2, >
[surch3] search-check(_EnvDescr, _TVListDescr, NOT _BooleanPrimary) =
         search-check(_EnvDescr, _TVListDescr, _BooleanPrimary)
[surch4] search-check(_EnvDescr, _TVListDescr, _Predicate) =
         <pred-check(_EnvDescr, _TVListDescr, _Predicate), >
[surch5] search-check(_EnvDescr, _TVListDescr, (_SearchCondition)) =
         search-check(_EnvDescr, _TVListDescr, _SearchCondition)

[sell1 ] sell-check(_EnvDescr, _TVListDescr, _Ident) =
         <_Error, [<_Ident, _DTDescr, NULL, [], false>]>
         when ve-check(_TVListDescr, _Ident) = <_Error, _DTDescr>
[sell2 ] sell-check(_EnvDescr, _TVListDescr, _Ident1._Ident2) =
         <_Error, [<_Ident2, _DTDescr, NULL, [], false>]>
         when ve-check(_TVListDescr, _Ident1._Ident2) = <_Error, _DTDescr>
[sell3 ] sell-check(_EnvDescr, _TVListDescr, _ValueExpr) =
         <_Error, [<_, _DTDescr, NULL, [], false>]>
         when ve-check(_TVListDescr, _ValueExpr) = <_Error, _DTDescr>
[sell4 ] sell-check(_EnvDescr, _TVListDescr, _ValueExpr, _ValueExpr+) =
```

```
          <_Error1 AND _Error2, [_ColDescr*1 _ColDescr*2]>
          when sell-check(_EnvDescr, _TVListDescr, _ValueExpr) = <_Error1, [_ColDescr*1]>,
               sell-check(_EnvDescr, _TVListDescr, _ValueExpr+) = <_Error2, [_ColDescr*2]>
 [sell5 ] sell-check(_EnvDescr, _TVListDescr, *) =
          <OK, get-column-descrs(_EnvDescr, _TVListDescr)>

 [gcds1 ] get-column-descrs(_EnvDescr, []) = []
 [gcds2 ] get-column-descrs(_EnvDescr, [_TVDescr _TVDescr*]) =
          [_ColDescr*1 _ColDescr*2]
          when get-column-descrs(_EnvDescr, _TVDescr) = [_ColDescr*1],
               get-column-descrs(_EnvDescr, [_TVDescr*]) = [_ColDescr*2]

 [gcd1  ] get-column-descrs(_EnvDescr, <_Ident1, _Ident2, _ColListDescr, _TConListDescr>) =
          _ColListDescr
 [gcd2  ] get-column-descrs(_EnvDescr, <_Ident1, _Ident2, _IdentList, _QuerySpec, _Bool>) =
          overlay-columns(_IdentList, _ColListDescr)
          when query-check(_EnvDescr, _QuerySpec) = <_Error, _Ident', _ColListDescr>

 [ovlcs1] overlay-columns([], []) = []
 [ovlcs2] overlay-columns([_Ident _Ident*], [_ColDescr _ColDescr*]) =
          [<_Ident, _DTDescr, _DefDescr, _CConListDescr, _Bool> _ColDescr*']
          when _ColDescr = <_Ident', _DTDescr, _DefDescr, _CConListDescr, _Bool>,
               overlay-columns([_Ident*], [_ColDescr*]) = [_ColDescr*']

 [subq1 ] subq-check(_EnvDescr, _TVListDescr, (SELECT ALL _ResultSpec _TableExpr)) =
          <_Error, A, _ColListDescr>
          when subq-check(_EnvDescr, _TVListDescr, (SELECT _ResultSpec _TableExpr)) =
               <_Error, _Ident, _ColListDescr>
 [subq2 ] subq-check(_EnvDescr, _TVListDescr, (SELECT DISTINCT _ResultSpec _TableExpr)) =
          <_Error, D, _ColListDescr>
          when subq-check(_EnvDescr, _TVListDescr, (SELECT _ResultSpec _TableExpr)) =
               <_Error, _Ident, _ColListDescr>
 [subq3 ] subq-check(_EnvDescr, _TVListDescr, (SELECT _ValueExpr _TableExpr)) =
          <_Error1 AND THEN _Error2, X, _ColListDescr>
          when texpr-check(_EnvDescr, _TVListDescr, _TableExpr) = <_Error1, _TVListDescr'>,
               sell-check(_EnvDescr, _TVListDescr', _ValueExpr) = <_Error2, _ColListDescr>
 [subq4 ] subq-check(_EnvDescr, _TVListDescr, (SELECT ALL * _TableExpr)) =
          subq-check(_EnvDescr, _TVListDescr, (SELECT * _TableExpr))
 [subq5 ] subq-check(_EnvDescr, _TVListDescr, (SELECT DISTINCT * _TableExpr)) =
          subq-check(_EnvDescr, _TVListDescr, (SELECT * _TableExpr))
 [subq6 ] subq-check(_EnvDescr, _TVListDescr, (SELECT * _TableExpr)) =
          <_Error1 AND THEN _Error2, X, _ColListDescr>
          when texpr-check(_EnvDescr, _TVListDescr, _TableExpr) = <_Error1, _TVListDescr'>,
               sell-check(_EnvDescr, _TVListDescr', *) = <_Error2, _ColListDescr>

end TC_Query_sem
```

```
module TC_QueryPred

imports

  TC_Pred_sem
  TC_Query_sem

exports

  context-free syntax

    tc "(" EnvDescr "," QuerySpec ")"                    -> ERROR

equations

[tc1] tc(_EnvDescr, _QuerySpec) =
      _Error
      when query-check(_EnvDescr, _QuerySpec) = <_Error, _Ident, _ColListDescr>

end TC_QueryPred
```

```
module TypeCheck

imports

  Errors
  SchemaCheck
  TC_QueryPred

exports

  context-free syntax

    tc "(" Environment "," QuerySpec ")"              -> ERROR

equations

[tc1] tc(_Environment, _QuerySpec) =
        tc(_EnvDescr')
          AND THEN
        tc(_EnvDescr', _QuerySpec)
      when
        env-descr(_Environment) = _EnvDescr,
        expand-env(_EnvDescr, _EnvDescr) = _EnvDescr'

end TypeCheck
```

```
module TR_Schema

imports

  Schemas
  RDBS

exports

  context-free syntax

    tr "(" Schema ")"                          -> SCHEMA
    tr "(" SchemaElement ")"                   -> SCHEMA
    tr "(" Ident ")"                           -> VAR
    attributes "(" {TableElement ","}+ ")"     -> VAR_TUP
    domains "(" {TableElement ","}+ ")"        -> REL
    domains "(" DataType ")"                   -> REL
    attributes "(" ViewColumnList ")"          -> VAR_TUP
    domains "(" QuerySpec ")"                  -> REL
    attributes "(" QuerySpec ")"               -> VAR_TUP

equations

[ 1] tr(CREATE SCHEMA AUTHORIZATION _Ident) =
     schema

[ 1] tr(CREATE SCHEMA AUTHORIZATION _Ident _SchemaElement _SchemaElement*) =
     schema _RDef*1 _RDef*2
     when tr(_SchemaElement) = schema _RDef*1,
          tr(CREATE SCHEMA AUTHORIZATION _Ident _SchemaElement*) = schema _RDef*2

[ 2] tr(CREATE TABLE _Ident1._Ident2 ( _TableElement+ )) =
     schema tr(_Ident2) <= { attributes(_TableElement+) @ domains(_TableElement+) }
[ 2] tr(CREATE TABLE _Ident2 ( _TableElement+ )) =
     schema tr(_Ident2)  <= { attributes(_TableElement+) @ domains(_TableElement+) }
[ 2] tr(CREATE VIEW _Ident1._Ident2 ( _ViewColumnList ) AS _QuerySpec WITH CHECK OPTION) =
     schema tr(_Ident2) <= { attributes(_ViewColumnList) @ domains(_QuerySpec) }
[ 2] tr(CREATE VIEW _Ident1._Ident2 ( _ViewColumnList ) AS _QuerySpec) =
     schema tr(_Ident2) <= { attributes(_ViewColumnList) @ domains(_QuerySpec) }
[ 2] tr(CREATE VIEW _Ident1._Ident2 AS _QuerySpec WITH CHECK OPTION) =
     schema tr(_Ident2) <= { attributes(_QuerySpec) @ domains(_QuerySpec) }
[ 2] tr(CREATE VIEW _Ident1._Ident2 AS _QuerySpec) =
     schema tr(_Ident2) <= { attributes(_QuerySpec) @ domains(_QuerySpec) }
[ 2] tr(CREATE VIEW _Ident2 ( _ViewColumnList ) AS _QuerySpec WITH CHECK OPTION) =
     schema tr(_Ident2) <= { attributes(_ViewColumnList) @ domains(_QuerySpec) }
[ 2] tr(CREATE VIEW _Ident2 ( _ViewColumnList ) AS _QuerySpec) =
     schema tr(_Ident2) <= { attributes(_ViewColumnList) @ domains(_QuerySpec) }
[ 2] tr(CREATE VIEW _Ident2 AS _QuerySpec WITH CHECK OPTION) =
     schema tr(_Ident2) <= { attributes(_QuerySpec) @ domains(_QuerySpec) }
[ 2] tr(CREATE VIEW _Ident2 AS _QuerySpec) =
     schema tr(_Ident2) <= { attributes(_QuerySpec) @ domains(_QuerySpec) }
[ 2] tr(_PrivilegeDef) = schema

[ 3] tr(ident(_Char+)) = var(_Char+)

[ 4] attributes(_TableElement, _TableElement+) =
     <_Vars1, _Vars2>
     when attributes(_TableElement) = <_Vars1>,
          attributes(_TableElement+) = <_Vars2>
[ 4] attributes(_Ident _DataType _DefaultClause _ColumnConstr*) =
     <tr(_Ident)>
[ 4] attributes(_Ident _DataType _ColumnConstr*) =
     <tr(_Ident)>
[ 4] attributes(_TableConstrDef) = < >

[ 5] domains(_TableElement, _TableElement+) =
     domains(_TableElement) # domains(_TableElement+)
[ 5] domains(_Ident _DataType _DefaultClause _ColumnConstr*) =
     domains(_DataType)
[ 5] domains(_Ident _DataType _ColumnConstr*) =
     domains(_DataType)

[ 6] domains(_StringType) = Strings
[ 6] domains(_ExactType) = Integers
[ 6] domains(_ApproxType) = Reals

[ 7] attributes(_Ident, _ColumnName+) =
     <_Var, _Vars>
     when tr(_Ident) = _Var,
          attributes(_ColumnName+) = <_Vars>
[ 7] attributes(_Ident) =
     <tr(_Ident)>

end TR_Schema
```

```
module TR_ValueExpr

imports

  ValueExpressions
  Expressions

exports

context-free syntax

    tr      "(" ValueExpr ")"          -> EXPR

equations

[ve1    ] tr(_ValueExpr + _Term) = tr(_ValueExpr) + tr(_Term)
[ve2    ] tr(_ValueExpr - _Term) = tr(_ValueExpr) - tr(_Term)
[ve3    ] tr(_Term * _Factor) = tr(_Term) * tr(_Factor)
[ve4    ] tr(_Term / _Factor) = tr(_Term) / tr(_Factor)
[ve5    ] tr(+ _Primary) = + tr(_Primary)
[ve6    ] tr(- _Primary) = - tr(_Primary)
[ve7    ] tr(_ParameterName INDICATOR _ParameterName') = null
%% case _ParameterName: see case _ColumnSpec
[ve8    ] tr(_EmbeddedVarName INDICATOR _EmbeddedVarName') = null
[ve9    ] tr(_EmbeddedVarName) = null
[ve10   ] tr(stringlit("'" _Char+ "'")) = str_const("'" _Char+ "'")
[ve11   ] tr(exactlit(_Char+)) = real_const(_Char+)
[ve12   ] tr(approxlit(_Char+)) = real_const(_Char+)
[ve13   ] tr(USER) = 'luit'
[ve14   ] tr(ident(_Char+1).ident(_Char+2)) = var(_Char+2)
[ve15   ] tr(ident(_Char+)) = var(_Char+)
[ve16   ] tr((_ValueExpr)) = tr(_ValueExpr)
[ve17   ] tr(_SetFuncSpec) = null

end TR_ValueExpr
```

```
module TR_QueryPred

imports

  TR_ValueExpr
  Predicates
  QuerySpecs
  Expressions
  RDBS

exports

  context-free syntax

    tr "(" Predicate ")"              -> EXPR
    tr "(" QuerySpec ")"              -> REL

  ddens

  context-free syntax

    tr-sell "(" SelectList ")"              -> EXPR_TUP
    tr-refs "(" {TableReference ","}+ ")"   -> REL
    tr-tref "(" TableReference ")"          -> VAR
    tr-srch "(" SearchCondition ")"         -> EXPR
    tr-subq "(" SubQuery ")"                -> REL

equations

[pred1 ] tr(_ValueExpr1 =  _ValueExpr2) = (tr(_ValueExpr1) =  tr(_ValueExpr2))
[pred1 ] tr(_ValueExpr1 <> _ValueExpr2) = (tr(_ValueExpr1) <> tr(_ValueExpr2))
[pred1 ] tr(_ValueExpr1 <  _ValueExpr2) = (tr(_ValueExpr1) <  tr(_ValueExpr2))
[pred1 ] tr(_ValueExpr1 >  _ValueExpr2) = (tr(_ValueExpr1) >  tr(_ValueExpr2))
[pred1 ] tr(_ValueExpr1 <= _ValueExpr2) = (tr(_ValueExpr1) <= tr(_ValueExpr2))
[pred1 ] tr(_ValueExpr1 >= _ValueExpr2) = (tr(_ValueExpr1) >= tr(_ValueExpr2))

[pred2 ] tr(_ValueExpr _CompOp _SubQuery) = tr(_ValueExpr _CompOp ALL _SubQuery)
[pred3 ] tr(_ValueExpr1 NOT BETWEEN _ValueExpr2 AND _ValueExpr3) =
         ! tr(_ValueExpr1 BETWEEN _ValueExpr2 AND _ValueExpr3)
[pred4 ] tr(_ValueExpr1 BETWEEN _ValueExpr2 AND _ValueExpr3) =
         (tr(_ValueExpr1) >= tr(_ValueExpr2)) & (tr(_ValueExpr1) <= tr(_ValueExpr3))
[pred5 ] tr(_ValueExpr IN _SubQuery) =
         <tr(_ValueExpr)> @ tr-subq(_SubQuery)
[pred6 ] tr(_ValueExpr IN _ValueSpec) =
         (tr(_ValueExpr) = tr(_ValueSpec))
[pred7 ] tr(_ValueExpr IN _ValueSpec, _ValueSpec+) =
         (tr(_ValueExpr) = tr(_ValueSpec)) | tr(_ValueExpr IN _ValueSpec+)
[pred8 ] tr(_ValueExpr NOT IN _SubQuery) =
         ! tr(_ValueExpr IN _SubQuery)
```

```
 [pred9 ] tr(_ValueExpr NOT IN _InValueList) =
          ! tr(_ValueExpr IN _InValueList)
 [pred10] tr(_ColumnSpec LIKE _ValueSpec1 ESCAPE _ValueSpec2) =
          null
 [pred11] tr(_ColumnSpec LIKE _ValueSpec) =
          null
 [pred12] tr(_ColumnSpec NOT LIKE _ValueSpec1 ESCAPE _ValueSpec2) =
          ! tr(_ColumnSpec LIKE _ValueSpec1 ESCAPE _ValueSpec2)
 [pred13] tr(_ColumnSpec NOT LIKE _ValueSpec) =
          ! tr(_ColumnSpec LIKE _ValueSpec)
 [pred14] tr(_ColumnSpec IS NULL) =
          (tr(_ColumnSpec) = null)
 [pred15] tr(_ColumnSpec IS NOT NULL) =
          ! tr(_ColumnSpec IS NULL)
 %% note: x cannot occur as SQL-ident (lower case not allowed)
 [pred16] tr(_ValueExpr = ALL _SubQuery) =
          for_all <x> @ tr-subq(_SubQuery) : (x = tr(_ValueExpr))
 [pred16] tr(_ValueExpr <> ALL _SubQuery) =
          for_all <x> @ tr-subq(_SubQuery) : (x <> tr(_ValueExpr))
 [pred16] tr(_ValueExpr < ALL _SubQuery) =
          for_all <x> @ tr-subq(_SubQuery) : (x > tr(_ValueExpr))
 [pred16] tr(_ValueExpr > ALL _SubQuery) =
          for_all <x> @ tr-subq(_SubQuery) : (x < tr(_ValueExpr))
 [pred16] tr(_ValueExpr <= ALL _SubQuery) =
          for_all <x> @ tr-subq(_SubQuery) : (x >= tr(_ValueExpr))
 [pred16] tr(_ValueExpr >= ALL _SubQuery) =
          for_all <x> @ tr-subq(_SubQuery) : (x <= tr(_ValueExpr))
 [pred16] tr(_ValueExpr = SOME _SubQuery) =
          there_is <x> @ tr-subq(_SubQuery) : (x = tr(_ValueExpr))
 [pred16] tr(_ValueExpr <> SOME _SubQuery) =
          there_is <x> @ tr-subq(_SubQuery) : (x <> tr(_ValueExpr))
 [pred16] tr(_ValueExpr < SOME _SubQuery) =
          there_is <x> @ tr-subq(_SubQuery) : (x > tr(_ValueExpr))
 [pred16] tr(_ValueExpr > SOME _SubQuery) =
          there_is <x> @ tr-subq(_SubQuery) : (x < tr(_ValueExpr))
 [pred16] tr(_ValueExpr <= SOME _SubQuery) =
          there_is <x> @ tr-subq(_SubQuery) : (x >= tr(_ValueExpr))
 [pred16] tr(_ValueExpr >= SOME _SubQuery) =
          there_is <x> @ tr-subq(_SubQuery) : (x <= tr(_ValueExpr))
 [pred16] tr(_ValueExpr _CompOp ANY _SubQuery) =
          tr(_ValueExpr _CompOp SOME _SubQuery)
 [pred17] tr(EXISTS _SubQuery) =
          # tr-subq(_SubQuery) <> 0

 [query1] tr(SELECT ALL _SelectList _TableExpr) =
          tr(SELECT      _SelectList _TableExpr)
 [query2] tr(SELECT DISTINCT _SelectList _TableExpr) =
          ! tr(SELECT           _SelectList _TableExpr)
 [query3] tr(SELECT _SelectList FROM _TableRefList WHERE _SearchCondition) =
          { tr-sell(_SelectList) <- @ tr-refs(_TableRefList) | tr-srch(_SearchCondition)}
          when _SelectList != *
 [query4] tr(SELECT _SelectList FROM _TableRefList) =
          { tr-sell(_SelectList) <- @ tr-refs(_TableRefList) | true}
          when _SelectList != *
 [query5] tr(SELECT * FROM _TableRefList WHERE _SearchCondition) =
          { @ tr-refs(_TableRefList) | tr-srch(_SearchCondition)}
 [query6] tr(SELECT * FROM _TableRefList) =
          { @ tr-refs(_TableRefList) | true}

 [sell1 ] tr-sell(_ValueExpr, _ValueExpr+) =
          <_Expr, _Exprs>
          when tr(_ValueExpr) = _Expr,
               tr-sell(_ValueExpr+) = <_Exprs>

 [trefl1] tr-refs(_Ident, _TableRefList) =
          tr-tref(_Ident) # tr-refs( _TableRefList)

 [trefl ] tr-tref(ident(_Char+)) = var(_Char+)

 [surch1] tr-srch(_SearchCondition OR _BooleanTerm) =
          tr-srch(_SearchCondition) | tr-srch(_BooleanTerm)
 [surch2] tr-srch(_BooleanTerm AND _BooleanFactor) =
          tr-srch(_BooleanTerm) & tr-srch(_BooleanFactor)
 [surch3] tr-srch(NOT _BooleanPrimary) =
          ! tr-srch(_BooleanPrimary)
 [surch4] tr-srch(_Predicate) =
          tr(_Predicate)
 [surch5] tr-srch((_SearchCondition)) =
          tr-srch(_SearchCondition)

 [subq1 ] tr-subq((SELECT ALL _ValueExpr _TableExpr)) =
          tr(SELECT  _ValueExpr _TableExpr)
 [subq2 ] tr-subq((SELECT DISTINCT _ValueExpr _TableExpr)) =
          tr(SELECT  _ValueExpr _TableExpr)

end TR_QueryPred
```