Advances in Data Management
Beyond records and objects
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1 Stored procedures and triggers

So far, we have been concerned with the storage of *data* in databases. However, modern DBMSs also allow *code* to be stored in the database.

Sequences of queries and updates can be bundled together into a **stored procedure** or *function* which is stored in the database and is available for subsequent execution.

To illustrate, suppose a relational database contains two relations
$Products(\underline{ProductID}, QuantityInStock, ReorderLevel)$
$NeedToReorder(\underline{ProductID}, ReorderQuantity)$

The following stored procedure (written in Oracle's PL/SQL language, which we will be looking at in more detail in an upcoming lab session) takes a product ID `p` and a quantity `q` (both numbers), finds out whether `p` is already on order, and if not it inserts the tuple `(p,q)` into the `NeedToReorder` relation:

```
CREATE PROCEDURE ReorderProduct(p,q NUMBER) AS
DECLARE AlreadyReordered NUMBER;
BEGIN
        SELECT COUNT(*) INTO AlreadyReordered
        FROM NeedToReorder
        WHERE ProductID = p;

        IF AlreadyReordered = 0
        THEN INSERT INTO NeedToReorder VALUES (p,q)
        ENDIF;
END;
```

Such stored procedures or functions can be called from within an SQL statement or from within another function or procedure. Stored functions can be used anywhere that SQL built-in functions can be used.

In addition to providing procedural abstraction, stored procedures/functions allow a block of SQL statements to be grouped into one statement that is submitted by the client application to the database server.

Generally, every SQL statement is executed individually by the database server. So grouping several statements together into one reduces client/server communication overheads and also network overheads if the client application and the database server are running on different machines. This has the potential to give considerable performance gains for applications.

The SQL/PSM (Persistent Stored Modules) standard specifies a language for defining stored procedures and functions. Its major elements include CREATE PROCEDURE and CREATE FUNC-

TION statements. Within the definitions of such procedures/functions, one can declare variables and use branching statements (IF ... THEN ... ELSEIF ... ELSE ... ENDIF), SQL statements, loops (LOOP ... END LOOP, WHILE ... DO ... END WHILE, REPEAT ... UNTIL ... END REPEAT). Similar features are provided by all modern commercial DBMSs, but in general not conforming precisely with the SQL/PSM syntax e.g. Oracle's PL/SQL language.

In modern DBMSs it is also possible to define **triggers** which will automatically execute some code if a specified event occurs in the database.

For example, the following trigger (written in Oracle's trigger syntax) is executed after any update of the QuantityInStock or ReorderLevel attributes of the Products relation.

It invokes the procedure `ReorderProduct` above for each product where the quantity in stock is now less than the reorder level:

```
CREATE TRIGGER ReorderTrigger
AFTER UPDATE OF QuantityInStock OR
                ReorderLevel
             ON Products
FOR EACH ROW
WHEN (new.QuantityInStock < new.ReorderLevel)
BEGIN
     CALL ReorderProduct(:new.ProductID,:new.ReorderLevel);
END;
```

(Variables declared in a PL/SQL host environment - such as SQL*Plus - and passed to PL/SQL as arguments must be prefixed with a colon.)

The following, alternative, trigger would be executed before any update of the QuantityInStock or ReorderLevel attributes of the Products relation. It would print out a warning message for any record for which the quantity in stock would have fallen below the reorder level and would reinstate the old values of these two attributes:

```
CREATE OR REPLACE TRIGGER ReorderTrigger
BEFORE UPDATE OF QuantityInStock OR
                ReorderLevel
             ON Products
FOR EACH ROW
WHEN (new.QuantityInStock < new.ReorderLevel)
BEGIN
     DBMS_OUTPUT.PUT_LINE('quantity in stock below reorder level for product '
     || :new.ProductID) ;
     DBMS_OUTPUT.PUT_LINE(' original values reinstated') ;
     :new.QuantityInStock := :old.QuantityInStock ;
     :new.ReorderLevel := :old.ReorderLevel ;
END;
```

1.1 Active Databases

Support of triggers turns databases from being *passive* to being *active*:

Passive databases execute transactions and queries that are explicitly submitted by users or applications.

Active databases can automatically react to occurrences of events and carry out appropriate actions.

Users specify the events to react to and the actions to carry out, by defining a set of *triggers*. A trigger consists of:

- An **event** part — the event that activates the trigger.
- A **condition** part — which is evaluated when the triggered is activated.
- An **action** part — which is executed if the condition is true.

So triggers are also known as **event-condition-action rules** (ECA rules).

The kinds of events that are detectable by typical RDBMSs are insertions, deletions, and updates on relations.

Some systems also support **composite events**, which are composed from primitive events using an 'event language' in which events can be combined by operators such as AND, OR, NOT, FOLLOWED_BY.

Triggers can be executed BEFORE, AFTER or INSTEAD OF the event that activates them.

Triggers can be:

- statement-level — the action part executes just once, provided the condition is true; or
- row-level — the action part executes for each row that was inserted/deleted/updated, and for which the condition is true.

The two versions of `ReorderTrigger` in Section 1 above are row-level triggers.

Here is an example of a statement-level trigger (written in the syntax specified by the SQL standard), assuming a relation $Students(studentId, name, address)$:

```
CREATE TRIGGER overRecruited
AFTER INSERT ON Students
REFERENCING NEW TABLE AS NewStudents
            OLD TABLE AS OldStudents
FOR EACH STATEMENT
WHEN (20000 < (SELECT COUNT(*)
               FROM NewStudents))

DELETE FROM Students
WHERE (studentId,name,address) IN NewStudents
  AND (studentId,name,address) NOT IN OldStudents;
```

```
INSERT INTO WaitingList (NewStudents EXCEPT OldStudents);
```

Note the use of NEW TABLE and OLD TABLE, and their aliases

The execution of one trigger can activate other triggers. This 'cascade' of activations continues until no more triggers are activated. In current commercial DBMSs there is a predefined limit on the number of such recursive activations, and if it is exceeded the current transaction is rolled back.

Much research has focussed on developing more sophisticated methods of detecting the termination properties of triggers, both statically (when triggers are defined) and dynamically (as triggers execute).

Applications of triggers include:

- detecting violation of complex integrity constraints and undertaking repair operations;
- enforcing complex authorisation restrictions;
- maintaining materialised views and replicas;
- logging particular events for auditing and security purposes;
- gathering statistics about database usage;
- notifying users or DBAs of the occurrence of particular database events.

2 Deductive Databases

Before SQL99, SQL did not support recursively defined relations.

For example, if we have a stored table `assembly` with attributes `Part`, `Subpart` and `Quantity`, recording the immediate subparts of parts, then it is not possible to write a (pre-SQL99) SQL query that returns all the components of a part unless the maximum depth of the part hierarchy is known, because we don't know how many times to join the `assembly` table with itself.

This limitation of SQL has led since the 1980s to research into *deductive databases*. These are databases which *do* support recursively defined derived relations. This research in turn led to the addition of recursion into SQL99.

The `WITH` statement in SQL99 allows the definition of derived relations:

$$\texttt{WITH}\ r\ \texttt{AS}\ d\ q$$

where r is the scheme of the derived relation, d is an SQL query defining the contents of r, and q is an SQL query using r.

If r appears within d (i.e. r is derived recursively), then the keyword `RECURSIVE` is required after `WITH`.

To illustrate, given a stored table `assembly(Part,Subpart,Quantity)`, we can find all the parts of which `P1` is a component as follows:

```
WITH RECURSIVE component(Part,Comp) AS
    (SELECT assemply.Part, assembly.Subpart
     FROM assembly)
     UNION
    (SELECT assembly.Part component.Comp
     FROM assembly, component
     WHERE assembly.Subpart = component.Part)
SELECT * FROM component WHERE Comp='P1'
```

Note that SQL's `WITH` introduces a relation which is available for use only *locally* within this statement — `component` does not become part of the database schema.

Only *stratified* definitions (see Section 4.3) are permitted in SQL99, both with respect to negation (e.g. `EXCEPT`, `NOT IN`, `NOT EXISTS`) and with respect to aggregation functions.

3 More on Deductive Databases

The bulk of research into deductive databases has used a language called **Datalog** to specify inference rules — Datalog is a subset of Prolog.

Returning to the example of the `assembly(Part,Subpart,Quantity)` table, we can specify as follows in Datalog a relation `component` that contains all pairs `(P,S)` such that `S` is a component of `P`, at any level in the parts hierarchy:

```
component(P,S) :- assembly(P,S,Q)
component(P,S) :- assembly(P,S1,Q), component(S1,S)
```

A Datalog rule has its *antecedents* on its right-hand side (RHS), and its *consequent* on its left-hand side (LHS). Any variable that appears in the consequent must also appear in the argument list of a (non-negated) predicate in the antecedent.

The first rule above states that, for every tuple `(P,S,Q)` in the `assembly` relation, we can infer that there is a tuple `(P,S)` in the `component` relation.

The second rule above states that, for every pair of tuples `(P,S1,Q)` in the `assembly` relation and `(S1,S)` in the `component` relation, we can infer that there is a tuple `(P,S)` in the `component` table.

Note that the above is a *recursive* definition of the derived relation `component` since the identifier `component` appears both on the LHS and the RHS of the second rule.

Other terms used for a **stored** relation are **base** relation or **extensional** relation; a **derived** relation is also known as an **intentional** relation.

A general method for evaluating derived relations in Datalog is as follows:

1. set the derived relation to be the empty set;

2. evaluate the rule(s) defining the relation using the current value of the derived relation in the RHS of the rule(s)

3. if there is any change to the derived relation return to step 2, else stop.

For recursive definitions, this is known as computing the **least fixpoint**.

To illustrate, suppose the `assembly` base relation is as follows:

assembly		
P5	P2	3
P5	P7	2
P2	P3	1
P2	P4	2
P7	P1	4
P1	P6	3
P1	P8	2
P1	P9	7

Then the first iteration of the evaluation procedure gives this as the definition of the `component` relation:

component_1	
P5	P2
P5	P7
P2	P3
P2	P4
P7	P1
P1	P6
P1	P8
P1	P9

The second iteration gives:

component_2	
P5	P2
P5	P7
P2	P3
P2	P4
P7	P1
P1	P6
P1	P8
P1	P9
P5	P3
P5	P4
P5	P1
P7	P6
P7	P8
P7	P9

The third iteration gives:

component_3	
P5	P2
P5	P7
P2	P3
P2	P4
P7	P1
P1	P6
P1	P8
P1	P9
P5	P3
P5	P4
P5	P1
P7	P6
P7	P8
P7	P9
P5	P6
P5	P8
P5	P9

The fourth iteration gives the same relation, and the evaluation stops.

3.1 Optimisation

The above evaluation method is rather naive as it performs redundant computations, and improvements are possible. One optimisation is to use **semi-naive** evaluation where only the new tuples inferred in each iteration are combined with the existing tuples.

Consider again these rules:

```
component(P,S) :- assembly(P,S,Q)
component(P,S) :- assembly(P,S1,Q), component(S1,S)
```

and the `assembly` base table as given earlier.

Initially, `component` is empty, so we apply just the first rule to compute the first increment to `component`, `delta_1`:

```
delta_1(P,S) :- assembly(P,S,Q)
```

Giving:

delta_1	
P5	P2
P5	P7
P2	P3
P2	P4
P7	P1
P1	P6
P1	P8
P1	P9

Thereafter, we use the second rule to compute successive increments to `component`, as follows:

```
delta_i+1(P,S) :- assembly(P,S1,Q), delta_i(S1,S)
```

Applying this rule for the first time, gives

delta_2	
P5	P3
P5	P4
P5	P1
P7	P6
P7	P8
P7	P9

Applying this rule for the second time, gives

delta_3	
P5	P6
P5	P8
P5	P9

Applying this rule for the third time gives `delta_4` $= \{\}$.

The evaluation therefore ends, giving `component` $=$ `delta_1` $\cup$ `delta_2` $\cup$ `delta_3`, which equals:

component	
P5	P2
P5	P7
P2	P3
P2	P4
P7	P1
P1	P6
P1	P8
P1	P9
P5	P3
P5	P4
P5	P1
P7	P6
P7	P8
P7	P9
P5	P6
P5	P8
P5	P9

3.2 Magic Sets (optional)

Another optimisation is known as **Magic Sets** and is useful for pushing selection conditions into a recursive definition to reduce the amount of computation — see Ramakrishnan and Gerhke 24.5.2 - 25.5.3 (optional reading).

For example, suppose we have `component` relation defined as follows:

```
component(P,S) :- assembly(P,S,Q)
component(P,S) :- assembly(P,S1,Q), component(S1,S)
```

The following Datalog queries respectively return: the whole component relation; the parts of which P3 is a component; the components of P1; and whether P3 is a component of P1:

```
component(P,S);
component(P,'P3');
component('P1',S);
component('P1','P3');
```

The Magic Sets optimisation approach would generate 4 different versions of the definition of `component`, each version optimised for a different combination of known/unknown information about the super-component and the sub-component.

The terms **bound** and **free** are used to indicate a known or unknown argument to a derived relation, respectively.

Here are the four definitions (which can be automatically generated from the original definition above):

Known super-component:

```
component_bf(P,S) :- assembly(P,S,Q)
component_bf(P,S) :- assembly(P,S1,Q), component_bf(S1,S)
```

Known sub-component:

```
component_fb(P,S) :- assembly(P,S,Q)
component_fb(P,S) :- assembly(P,S1,Q), component_bb(S1,S)
```

Known super-component and sub-component:

```
component_bb(P,S) :- assembly(P,S,Q)
component_bb(P,S) :- assembly(P,S1,Q), component_bb(S1,S)
```

Unknown super-component and sub-component:

```
component_ff(P,S) :- assembly(P,S,Q)
component_ff(P,S) :- assembly(P,S1,Q), component_bf(S1,S)
```

The 4 queries above can then be optimised by using the appropriate definition:

```
component_ff(P,S);
component_fb(P,'P3');
component_bf('P1',S);
component_bb('P1','P3');
```

3.3 Left, right and nonlinear recursion (optional)

The above definition of the derived relation `component` is called **right-recursive** since the base relation `assembly` appears first within the second rule:

```
component(P,S) :- assembly(P,S,Q)
component(P,S) :- assembly(P,S1,Q),component(S1,S)
```

The following **left-recursive** definition would give the same answer [exercise for the reader]:

```
component(P,S) :- assembly(P,S,Q)
component(P,S) :- component(P,S1),assembly(S1,S,Q)
```

Right- and left-recursion are both examples of **linear** recursion, where the derived relation appears only once in the RHS of the definition. **Nonlinear** recursion is also possible. For example, this definition gives the same answer as the two above definitions [exercise for the reader]:

```
component(P,S) :- assembly(P,S,Q)
component(P,S) :- component(P,S1),component(S1,S)
```

3.4 Negation in Recursive Definitions (optional)

Introducing negation into recursive definitions can cause problems. For example, consider the following definitions:

```
big(P)   :- assembly(P,S,Q), NOT small(P)
small(P) :- assembly(P,S,Q), NOT big (P)
```

What is the value of `big` and `small` ?

Well, following the evaluation method described above,
$big_0 = small_0 = \{\}$
$big_1 = small_1 =$ assembly
$big_2 = small_2 = \{\}$
$big_3 = small_3 =$ assembly
etc. and the computation fails to terminate. This is because there is no single least fixpoint answer for the above definitions.

The solution to this problem is to disallow ambiguous definitions such as that above by requiring that definitions are **stratified**:

Construct a graph (known as the **dependency graph**) whose nodes are the derived relations. Draw an arc from R to S if S appears in the definition of R. Label this arc with a '+' if S appears non-negated and label it with a '-' if S appears negated.

The set of definitions is **stratified** if there no cycles labelled with '-' on any of their arcs.

The relations defined by a stratified set of definitions can be divided into strata 0, 1, 2 ... such that the relations in stratum i depend positively only on relations in strata $j \leq i$ and depend negatively only on relations in strata $j < i$.

A stratified set of definitions can be evaluated stratum by stratum to give an unambiguous result.

Aggregation functions can pose similar problems to negation in recursive definitions, because the incremental computation of an aggregation function invalidates the previous iteration's computation.

For example, suppose we have a single-column base table p, containing three tuples 1, 2, 3. And a new derived relation, r, is defined by the following (non-stratified) rules:

```
r(X) :- p(X)
r(X) :- X is sum(r)
```

Then: $r_0 = \{\}$
$r_1 = \{1, 2, 3, 0\}$
$r_2 = \{1, 2, 3, 6\}$
$r_3 = \{1, 2, 3, 12\}$
etc., and the computation never reaches a fixpoint.

In general, derived relations need to be `monotonic` i.e. only new tuples can be added at each round of their evaluation and tuples computed in a previous round cannot be made invalid.

3.5 Influence

The theoretical foundations of Datalog, together with the semi-native and Magic Sets techniques pioneered in the context of that language, underlie the evaluation of recursively-defined relations and queries in modern-day DBMSs, as well as in specialised rule-based systems for reasoning with data in a variety of settings e.g. systems that combine RDFS/OWL reasoning with relational data management or with graph data.

Homework 3 (optional)

Consider a database for the London underground and bus network, consisting of two relations:

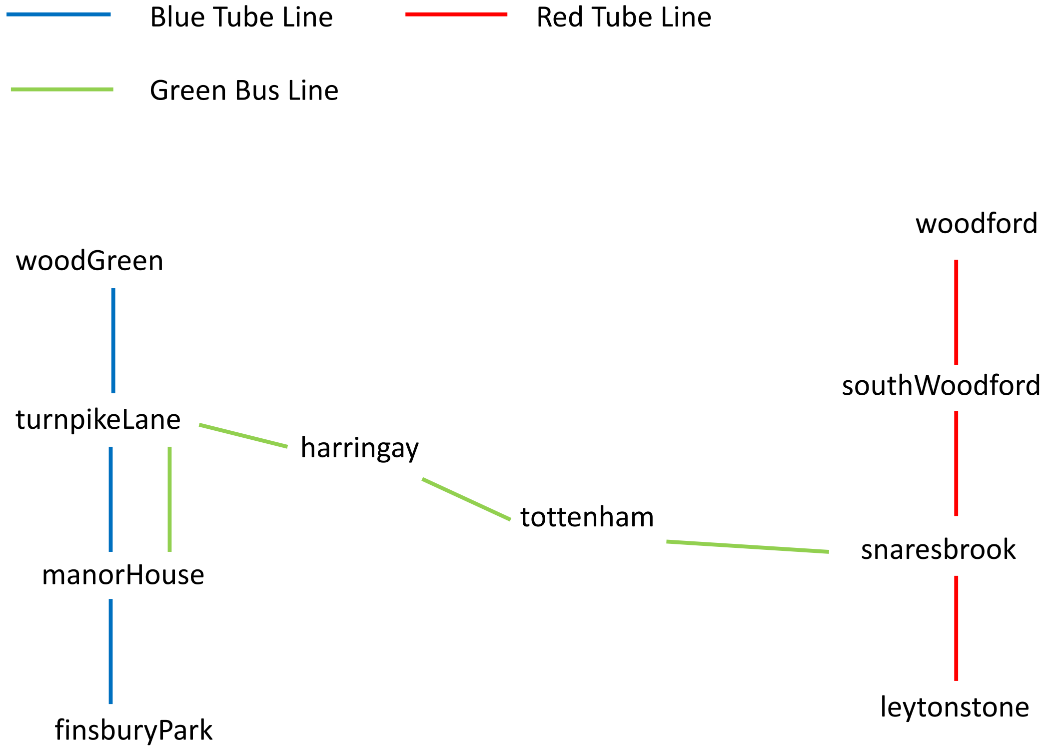
```
tube(Station,NextStation,TubeLine)
bus(Station,NextStation,BusLine)
```

With contents:

tube		
finsuryPark	manorHouse	blueLine
manorHouse	finsburyPark	blueLine
manorHouse	turnpikeLane	blueLine
turnpikeLane	manorHouse	blueLine
turnpikeLane	woodGreen	blueLine
woodGreen	turnpikeLane	blueLine
leytonstone	snaresbrook	redLine
snaresbrook	leytonstone	redLine
snaresbrook	southWoodford	redLine
southWoodford	snaresboork	redLine
southWoodford	woodford	redLine
woodford	southWoodford	redLine

bus		
manorHouse	turnpikeLane	greenLine
turnpikeLane	manorHouse	greenLine
turnpikeLane	harringay	greenLine
harringay	turnpikeLane	greenLine
harringay	tottenham	greenLine
tottenham	harringay	greenLine
tottenham	walthamstow	greenLine
walthamstow	tottenham	greenLine
walthamstow	snaresbrook	greenLine
snaresbrook	walthamstow	greenLine

Diagrammatically, we can present this route map as shown in the figure.


Blue Tube Line
Red Tube Line
Green Bus Line
woodford
woodGreen
southWoodford
turnpikeLane
harringay
tottenham
snaresbrook
manorHouse
leytonstone
finsburyPark

Write derived relation definitions in Datalog that give the following:

1. The pairs of stations A,B such that B is reachable from A by tube.
2. The pairs of stations A,B such that B is reachable from A by bus.
3. The pairs of stations A,B such that B is reachable from A by tube but not by bus.
4. The pairs of stations A,B such that B is reachable from A by some combination of tube or bus.
5. The pairs of stations A,B such that B is reachable from A by some combination of tube or bus, but not by tube or bus alone.