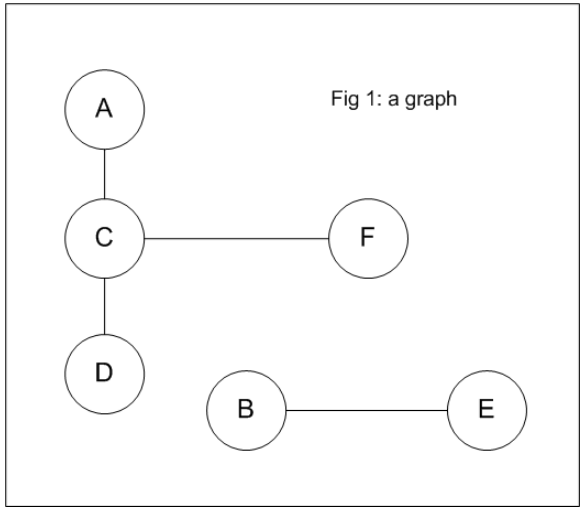
Trees and Other Hierarchies in MySQL

Most non-trivial data is hierarchical. Customers have orders, which have line items, which refer to products, which have prices. Population samples have subjects, who take tests, which give results, which have sub-results and norms. Web sites have pages, which have links, which collect hits across dates and times. These are *hierarchies of tables.* The number of tables limits the number of JOINs needed to walk the tree. For such queries, conventional SQL is an excellent tool.

But when tables map a family tree, or a browsing history, or a bill of materials, *table rows relate hierarchically to other rows in the same table*. We no longer know how many JOINs we need to walk the tree. We need a different data model.



That model is the *graph* (Fig 1), which is a set of *nodes* (vertices) and the *edges* (lines or arcs) that connect them. This chapter is about how to model and query graphs in a MySQL database.

Graph theory is a branch of topology, the study of geometric relations that aren't changed by stretching and compression—rubber sheet geometry, some call it. Graph theory is ideal for modelling hierarchies—like family trees, browsing histories, search trees, Bayesian networks and bills of materials—whose shape and size we can't know in advance.

Let the set of nodes in Fig 1 be `N`, the set of edges be `L`, and the graph be `G`. Then `G` is the tuple or ordered pair `{N,L}`:

```
N = {A,B,C,D,E,F}
L = {AC,CD,CF,BE}
G = {N,L}
```

If the edges are *directed*, the graph is a *digraph* or directed graph. A *mixed graph* has both directed and undirected edges.

Examples of graphs are organisational charts; itineraries; route maps; parts explosions; massively multiplayer games; language rules; chat histories; network and link analysis in a wide variety of fields, for example search engines, forensics, epidemiology and telecommunications; data mining; models of chemical structure hierarchies; and *biochemical processes*.

Graph characteristics and models

Nodes and edges : Two nodes are *adjacent* if there is an edge between them. Two edges are adjacent if they connect to a common node. In a *complete graph*, all nodes are adjacent to all other nodes.

In a digraph, the number of edges entering a node is its *indegree*; the number leaving is its *outdegree*. A node of indegree zero is a *root node*, a node of outdegree zero is a *leaf node*.

In a *weighted graph*, used for example to solve the travelling salesman problem, edges have a weight attribute. A digraph with weighted edges is a *network*.

Paths and cycles: A connected sequence of edges is a *path*, its length the edge count. Two nodes are connected if there is a path between them. If there is a path connecting every pair of nodes, the graph is a *connected graph*.

A path in which no node repeats is a *simple path*. A path that returns to its own origin without crossing itself is a *cycle* or circuit. A graph with multiple paths between at least one pair of nodes is *reconvergent*. A reconvergent graph may be *cyclic* or *acyclic*. A unit length cycle is a *loop*.

If a graph's edges intersect only at nodes, it is *planar*. Two paths having no node in common are *independent*.

Traversing graphs: There are two main approaches, *breadth-first* and *depth-first*. Breadth-first traversal visits all a node's siblings before moving on to the next level, and typically uses a *queue*. Depth-first traversal follows edges down to leaves and back before proceeding to siblings, and typically uses a *stack*.

Sparsity: A graph where the size of E approaches the maximum N^2 is *dense*. When the multiple is much smaller than N, the graph is considered *sparse*.

Trees: A *tree* is a connected graph with no cycles. It is also a graph where the indegree of the root node is 0, and the indegree of every other node is 1. A tree where every node is of outdegree <=2 is a *binary tree*. A *forest* is a graph where every connected component is a tree.

Euler paths: A path which traverses every edge in a graph exactly once is an *Euler path*. An Euler path which is a circuit is an *Euler circuit*.

If and only if every node of a connected graph has even degree, it has an *Euler circuit* (which is *why* the good people of Königsberg cannot go for a walk crossing each of their seven bridges exactly once). If and only if a connected graph has exactly 2 nodes with odd degree, it has a *non-circuit Euler path*. The degree of an endpoint of a non-cycle Euler path is 1 + twice the number of times the path passes through that node, so it is always odd.

Models for computing graphs

Traditionally, computer science textbooks have offered *edge lists*, *adjacency lists* and *adjacency matrices* as data structures for graphs, with algorithms implemented in languages like C, C++ and Java. More recently other models and tools have been suggested, including query languages customised for graphs.

Edge list: The simplest way to represent a graph is to list its edges: for Fig 1, the edge list is `{AC,CD,CF,BE}`. It is easy to add an edge to the list; deletion is a little harder.

Table 20-1: An Adjacency List

Nodes	*Adjacent nodes*
A	C
B	E
C	F,D,A
D	C
E	B
F	C

Adjacency list: An *adjacency list* is a ragged array: for each node it lists all adjacent nodes. Formally, it represents a directed graph of *n* nodes as a list of *n* lists where list *i* contains node *j* if the graph has an edge from node *i* to node *j*.

An undirected graph may be represented by having node *j* in the list for node *i*, and node *i* in the list for node *j*. Table 20-1 shows the adjacency list of the graph in Fig 1 interpreted as undirected.

Adjacency matrix: An *adjacency matrix* represents a graph with *n* nodes as an *n* x *n* matrix, where entry *(i,j)* is 1 node *i* has an edge to node *j*, or zero if there is not. An adjacency matrix can represent a weighted graph using the weight as the entry, and can represent an undirected graph by duplicating entries in *(i,j)* anf *(j,i)*. or by using a triangular matrix.

There are useful glossaries *here* and *here*.

Graphs and SQL

Standard SQL has been cumbersome for the recursive row-to-row logic of graphs. To fix this, DB2, Oracle, SQL Server and PostgreSQL have added recursive Common Table Expressions (CTEs). Until 8.0, MySQL hasn't had CTEs, so recursive graph logic required stored routines. *MariaDB has had CTEs since version 10.2.2*, *MySQL since 8.0.2*. Joe Celko and Scott Stephens, among others, have published general SQL graph problem solutions that are simpler and smaller than equivalent C++, C# or Java code. Here we show how to use such tools.

Beware that in ports of *edge list* methods to SQL, there has been name slippage. What SQLers often call an adjacency list isn't like the adjacency list shown in Table 1; *it's an edge list*. Here we'll honour that fact, and mostly call them edge lists, but to keep the peace we'll sometimes call them *edge-adjacency lists*.

Joe Celko calls his method *nested sets*. It's an *interval model*, using greater-than/less-than arithmetic to encode tree relationships and modified preorder tree traversal (MPTT) to query them. Tropashko's *materialised path* model stores each node with its (denormalised) path to the root. So now we have five main ways to model graphs in MySQL:

- *edge-adjacency lists*: based on an adaptation by EF Codd of the logic of linked lists to table structures and queries,
- *adjacency matrices*,
- *nested sets* for trees simplify some queries, but tree updates are extremely inefficient,
- *materialised paths*,
- *recursive CTEs*.

The edge list

The edge list is the simplest possible SQL representation of a graph: minimally, a single edges table where each row specifies one node and its parent (which is NULL for the root node), or to avoid *DKNF* problems, two tables: one for the *nodes*, the other for their *edges*.

In the real world, the nodes table might be a table of personnel, or assembly parts, or locations on a map. It might have many other columms of data. The edges table might also have additional columns for edge properties. The key integers of both tables might be BIGINTs. To model *Fig 1*, though, we keep things as simple as possible:

Listing 1

```
CREATE TABLE nodes(nodeID CHAR(1) PRIMARY KEY);
CREATE TABLE edges(
  childID CHAR(1) NOT NULL,
  parentID CHAR(1) NOT NULL,
  PRIMARY KEY(childID,parentID)
);
INSERT INTO nodes VALUES('A'), ('B'), ('C'), ('D'), ('E'), ('F');
INSERT INTO edges VALUES ('A','C'), ('C','D'), ('C','F'), ('B','E');
SELECT * FROM edges;
+---------+----------+
| childID | parentID |
+---------+----------+
| A       | C        |
| B       | E        |
| C       | D        |
| C       | F        |
+---------+----------+
```

Now, without any assumptions about whether the graph is connected, whether it is directed, whether it is a tree, or whatever, how hard is it to write a *reachability* procedure, a procedure which tells us *where we can get to from here*, wherever 'here' is? A simple approach is a breadth-first *search*:

1. Seed the list with the starting node,

2. Add, but do not duplicate, nodes which are children of nodes in the list,
3. Add, but do not duplicate, nodes which are parents of nodes in the list,
4. Repeat steps 2 and 3 until there are no more nodes to add.

Here it is as a MySQL stored procedure. It avoids duplicate nodes by defining `reached.nodeID` as a primary key and adding reachable nodes with `INSERT IGNORE`:

Listing 2

```
DROP PROCEDURE IF EXISTS ListReached;
DELIMITER go
CREATE PROCEDURE ListReached( IN root CHAR(1) )
BEGIN
  DECLARE rows SMALLINT DEFAULT 0;
  DROP TABLE IF EXISTS reached;
  CREATE TABLE reached ( nodeID CHAR(1) PRIMARY KEY ) ENGINE=HEAP;
  INSERT INTO reached VALUES (root );
  SET rows = ROW_COUNT();
  WHILE rows > 0 DO
    INSERT IGNORE INTO reached
      SELECT DISTINCT childID FROM edges AS e
      JOIN reached AS p ON e.parentID = p.nodeID;
    SET rows = ROW_COUNT();
    INSERT IGNORE INTO reached
      SELECT DISTINCT parentID FROM edges AS e
      JOIN reached AS p ON e.childID = p.nodeID;
    SET rows = rows + ROW_COUNT();
  END WHILE;
  SELECT Group_Concat(nodeID) FROM reached;
  DROP TABLE reached;
END;
go
DELIMITER ;
CALL ListReached('A');  -- returns A,B,C,D
```

To make the procedure more versatile, give it input parameters to tell it whether to list child, parent or all connections, and whether to recognise loops (for example C to C).

To give the model referential integrity, use InnoDB and make `edges.childID` and `edges.parentID` foreign keys. To add or delete a node, add or delete desired single rows in `nodes` and `edges`. To change an edge, edit it. The model neither requires the graph to be connected or treelike, nor presumes direction.

Edge list model of a tree

The SQL literature on graphs often gives solutions using single denormalised tables, but denormalisation can cost, big time. The bigger the table, the bigger the cost. You cannot edit nodes and edges separately. Carrying extra node info during edge computation slows performance.

To avoid such difficulties, normalise trees like William Shakespeare's family tree (Fig 2) into two tables, *nodes* (`family`) with a row for each individual's data, and *edges* (`familytree`) with a row for each parent-child link or *edge*.

Listing 3:

```
CREATE TABLE family( ID smallint unsigned PRIMARY KEY AUTO_INCREMENT, name char(20) default '',
  siborder tinyint default NULL, born smallint unsigned default NULL, died smallint unsignedefault NULL );
INSERT INTO family VALUES (1, 'Richard Shakespeare', NULL, NULL, 1561),
(2, 'Henry Shakespeare', 1, NULL, 1569),(3, 'John Shakespeare', 2, 1530, 1601),
(4, 'Joan Shakespeare', 1, 1558, NULL),(5, 'Margaret Shakespeare', 2, 1562, 1563),
(6, 'William Shakespeare', 3, 1564, 1616),(7, 'Gilbert Shakespeare', 4, 1566, 1612),
(8, 'Joan Shakespeare', 5, 1568, 1646),(9, 'Anne Shakespeare', 6, 1571, 1579),
(10, 'Richard Shakespeare', 7, 1574, 1613),(11, 'Edmond Shakespeare', 8, 1580, 1607),
(12, 'Susana Shakespeare', 1, 1583, 1649),(13, 'Hamnet Shakespeare', 1, 1585, 1596),
(14, 'Judith Shakespeare', 1, 1585, 1662),(15, 'William Hart', 1, 1600, 1639),
(16, 'Mary Hart', 2, 1603, 1607),(17, 'Thomas Hart', 3, 1605, 1670),
(18, 'Michael Hart', 1, 1608, 1618),(19, 'Elizabeth Hall', 1, 1608, 1670),
(20, 'Shakespeare Quiney', 1, 1616, 1617),(21, 'Richard Quiney', 2, 1618, 1639),
(22, 'Thomas Quiney', 3, 1620, 1639),(23, 'John Bernard', 1, NULL, 1674);
CREATE TABLE familytree(
  childID smallint unsigned NOT NULL,parentID smallint unsigned NULL,PRIMARY KEY(childID, parentID) );
INSERT INTO familytree VALUES (2,1),(3,1),(4,2),(5,2),(6,2),(7,2),(8,2),(9,2),(10,2),(11,2),(12,6),(13,6),
                      (14,6),(15,8),(16,8),(17,8),(18,8),(19,12),(20, 14),(21, 14),(22, 14),(23, 19);
```

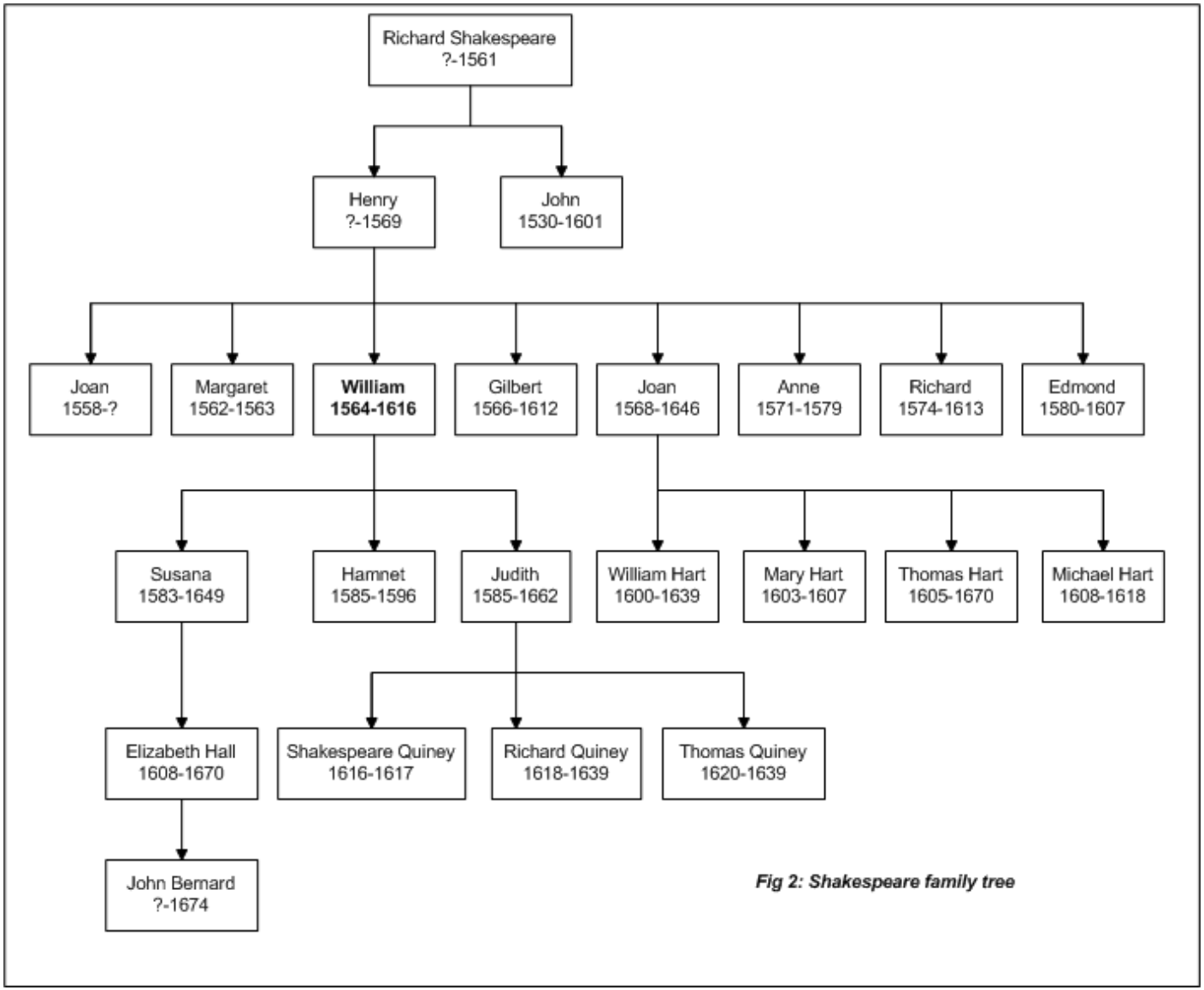


Fig 2: Shakespeare family tree

A function to return `family.name` for a `familytree childID` or `parentID`:

Listing 4

```
DROP FUNCTION IF EXISTS PersonName;
CREATE FUNCTION PersonName(pid smallint) RETURNS VARCHAR(20) DETERMINISTIC
RETURN (SELECT name FROM family WHERE ID=pid);
SELECT PersonName( parentID ) AS 'Parent of William' FROM familytree WHERE childID = 6;
+-------------------+
| Parent of William |
+-------------------+
| Henry Shakespeare |
+-------------------+
SELECT PersonName( childID ) AS 'Children of William' FROM familytree
WHERE parentID = (SELECT ID FROM family WHERE name = 'William Shakespeare');
+---------------------+
| Children of William |
+---------------------+
| Susana Shakespeare  |
| Hamnet Shakespeare  |
| Judith Shakespeare  |
+---------------------+
SELECT PersonName(childID) AS child, PersonName(parentID) AS parent FROM familytree;
+----------------------+---------------------+
| child                | parent              |
+----------------------+---------------------+
| Henry Shakespeare    | Richard Shakespeare |
| John Shakespeare     | Richard Shakespeare |
| Joan Shakespeare     | Henry Shakespeare   |
| Margaret Shakespeare | Henry Shakespeare   |
| William Shakespeare  | Henry Shakespeare   |
| Gilbert Shakespeare  | Henry Shakespeare   |
| Joan Shakespeare     | Henry Shakespeare   |
| Anne Shakespeare     | Henry Shakespeare   |
| Richard Shakespeare  | Henry Shakespeare   |
| Edmond Shakespeare   | Henry Shakespeare   |
| Susana Shakespeare   | William Shakespeare |
| Hamnet Shakespeare   | William Shakespeare |
| Judith Shakespeare   | William Shakespeare |
```

```
| William Hart          | Joan Shakespeare    |
| Mary Hart             | Joan Shakespeare    |
| Thomas Hart           | Joan Shakespeare    |
| Michael Hart          | Joan Shakespeare    |
| Elizabeth Hall        | Susana Shakespeare  |
| Shakespeare Quiney    | Judith Shakespeare  |
| Richard Quiney        | Judith Shakespeare  |
| Thomas Quiney         | Judith Shakespeare  |
| John Bernard          | Elizabeth Hall      |
+-----------------------+---------------------+
```

A same-table foreign key can simplify tree maintenance:

Listing 4a:

```
create table edges (
  ID int PRIMARY KEY, parentid int,
  foreign key(parentID) references edges(ID) ON DELETE CASCADE ON UPDATE CASCADE
) engine=innodb;
insert into edges(ID,parentID) values (1,null),(2,1),(3,1),(4,2);
select * from edges;
+----+----------+
| ID | parentid |
+----+----------+
|  1 |     NULL |
|  2 |        1 |
|  3 |        1 |
|  4 |        2 |
+----+----------+
delete from edges where id=2;
select * from edges;
+----+----------+
| ID | parentid |
+----+----------+
|  1 |     NULL |
|  3 |        1 |
+----+----------+
```

Simple queries retrieve basic facts about the tree, for example GROUP_CONCAT() collects parent nodes with their children:

Listing 5

```
SELECT parentID AS Father, GROUP_CONCAT(childID ORDER BY siborder) AS Children
FROM familytree t
JOIN family f ON t.parentID=f.ID
GROUP BY parentID;
+--------+-------------------+
| Father | Children          |
+--------+-------------------+
|      1 | 3,2               |
|      2 | 4,5,6,7,8,9,10,11 |
|      6 | 12,13,14          |
|      8 | 18,17,16,15       |
|     12 | 19                |
|     14 | 22,21,20          |
|     19 | 23                |
+--------+-------------------+
```

Iterate over those child lists with a bit of application code and you have a hybrid treewalk. The *paterfamilias* is the root node, childless individuals are leaf nodes, and queries to retrieve subtree statistics are straightforward:

Listing 6

```
SELECT PersonName(ID) AS Paterfamilias,IFNULL(born,'?') AS Born,IFNULL(died,'?') AS Died
FROM family AS f LEFT JOIN familytree AS t ON f.ID=t.childID
WHERE t.childID IS NULL;
+---------------------+------+------+
| Paterfamilias       | Born | Died |
+---------------------+------+------+
| Richard Shakespeare | ?    | 1561 |
+---------------------+------+------+
SELECT PersonName(ID) AS Childless,IFNULL(born,'?') AS Born,IFNULL(died,'?') AS Died
FROM family AS f
LEFT JOIN familytree AS t ON f.ID=t.parentID
WHERE t.parentID IS NULL;
+----------------------+------+------+
| Childless            | Born | Died |
+----------------------+------+------+
| John Shakespeare     | 1530 | 1601 |
| Joan Shakespeare     | 1558 | ?    |
```

```
| Margaret Shakespeare | 1562 | 1563 |
| Gilbert Shakespeare  | 1566 | 1612 |
| Anne Shakespeare     | 1571 | 1579 |
| Richard Shakespeare  | 1574 | 1613 |
| Edmond Shakespeare   | 1580 | 1607 |
| Hamnet Shakespeare   | 1585 | 1596 |
| William Hart         | 1600 | 1639 |
| Mary Hart            | 1603 | 1607 |
| Thomas Hart          | 1605 | 1670 |
| Michael Hart         | 1608 | 1618 |
| Shakespeare Quiney   | 1616 | 1617 |
| Richard Quiney       | 1618 | 1639 |
| Thomas Quiney        | 1620 | 1639 |
| John Bernard         | ?    | 1674 |
+----------------------+------+------+
```

```
SELECT ROUND(AVG(died-born),2) AS 'Longevity of the childless'
FROM family AS f
LEFT JOIN familytree AS t ON f.ID=t.parentID
WHERE t.parentID IS NULL;    -- returns 25.86
```

In striking contrast with Celko's *nested sets model*, inserting a new item in this model requires *no* revision of existing rows. We just add a new `family` row, then a new `familytree` row with IDs specifying who is parent to whom. Deletion is also a two-step: delete the `familytree` row for that child-parent link, then delete the `family` row for that child.

Walking an edge list tree or subtree

Edge list tree traversal is supposed to be difficult. Usually we don't know how many levels must be traversed, so the query needs recursion or a logically equivalent loop. Without CTEs (*i.e.*, before MySQL 8.0.1 or MariaDB 10.2.2), that requires a stored procedure. We start with a *breadth-first* algorithm, a simple one that just seeds a result table with children of the root node, then adds remaining edges with INSERT IGNORE:

Listing 7

```
DELIMITER go
CREATE PROCEDURE famsubtree( root INT )
BEGIN
  DROP TABLE IF EXISTS famsubtree;
```

```
  CREATE TABLE famsubtree( childID smallint unsigned not null, parentID smallint unsigned null,
                           Primary Key(childID,parentID) )
    SELECT childID, parentID, 0 AS level FROM familytree WHERE parentID = root;
  REPEAT
    INSERT IGNORE INTO famsubtree
      SELECT f.childID, f.parentID, s.level+1
      FROM familytree AS f
      JOIN famsubtree AS s ON f.parentID = s.childID;
  UNTIL Row_Count() = 0 END REPEAT;
END go
DELIMITER ;
call famsubtree(1);
SELECT Concat(Space(level),parentID) AS Parent, Group_Concat(childID ORDER BY childID) AS Child
FROM famsubtree
GROUP BY parentID;
+--------+-------------------+
| Parent | Child             |
+--------+-------------------+
| 1      | 2,3               |
|  2     | 4,5,6,7,8,9,10,11 |
|   6    | 12,13,14          |
|   8    | 15,16,17,18       |
|    12  | 19                |
|    14  | 20,21,22          |
|     19 | 23                |
+--------+-------------------+
```

Simple and quick. *The logic ports to any edge list.* We can prove that right now by writing a generic version. GenericTree() just needs parameters for the name of the target table, the names of its child and parent ID columns, and the parent ID whose descendants are sought:

Listing 7a: General-purpose edge list treewalk

```
CREATE PROCEDURE GenericTree(
  edgeTable CHAR(64), edgeIDcol CHAR(64), edgeParentIDcol CHAR(64), ancestorID INT )
BEGIN
  DECLARE r INT DEFAULT 0;
  DROP TABLE IF EXISTS subtree;
  SET @sql = Concat( 'CREATE TABLE subtree  SELECT ',
```

```
                    edgeIDcol,' AS childID, ',
                    edgeParentIDcol, ' AS parentID,',
                    '0 AS level FROM ',
                    edgeTable, ' WHERE ', edgeParentIDcol, '=', ancestorID );
  PREPARE stmt FROM @sql;
  EXECUTE stmt;
  DROP PREPARE stmt;
  ALTER TABLE subtree ADD PRIMARY KEY(childID,parentID);
  REPEAT
    SET @sql = Concat( 'INSERT IGNORE INTO subtree SELECT a.', edgeIDcol,
                      ',a.',edgeparentIDcol, ',b.level+1 FROM ',
                      edgeTable, ' AS a JOIN subtree AS b ON a.',edgeParentIDcol, '=b.childID' );
    PREPARE stmt FROM @sql;
    EXECUTE stmt;
    SET r=Row_Count();  -- save row_count() result before DROP PREPARE loses the value
    DROP PREPARE stmt;
  UNTIL r < 1 END REPEAT;
END ;
```

To retrieve details like names and other data associated with node IDs, write a frontend query to join the `subtree` result table with the required detail table(s), for example:

```
CALL GenericTree('familytree','childID','parentID',1);
SELECT Concat(Repeat( ' ', s.level), a.name ) AS Parent, b.name AS Child
FROM subtree s
JOIN family a ON s.parentID=a.ID
JOIN family b ON s.childID=b.ID;
+----------------------+----------------------+
| Parent               | Child                |
+----------------------+----------------------+
| Richard Shakespeare  | Henry Shakespeare    |
| Richard Shakespeare  | John Shakespeare     |
|  Henry Shakespeare   | Joan Shakespeare     |
|  Henry Shakespeare   | Margaret Shakespeare |
|  Henry Shakespeare   | William Shakespeare  |
|  Henry Shakespeare   | Gilbert Shakespeare  |
|  Henry Shakespeare   | Joan Shakespeare     |
|  Henry Shakespeare   | Anne Shakespeare     |
```

```
|  Henry Shakespeare    | Richard Shakespeare  |
|  Henry Shakespeare    | Edmond Shakespeare   |
|   William Shakespeare | Susana Shakespeare   |
|   William Shakespeare | Hamnet Shakespeare   |
|   William Shakespeare | Judith Shakespeare   |
|   Joan Shakespeare    | William Hart         |
|   Joan Shakespeare    | Mary Hart            |
|   Joan Shakespeare    | Thomas Hart          |
|   Joan Shakespeare    | Michael Hart         |
|    Susana Shakespeare | Elizabeth Hall       |
|    Judith Shakespeare | Shakespeare Quiney   |
|    Judith Shakespeare | Richard Quiney       |
|    Judith Shakespeare | Thomas Quiney        |
|     Elizabeth Hall    | John Bernard         |
+-----------------------+----------------------+
```

Is GenericTree() fast? On standard hardware it walks a 5,000-node tree in less than 0.5 secs—*much faster than a comparable* nested sets *query on the same tree!* It has no serious scaling issues. And its logic can be used to prune: call GenericTree() then delete the listed rows. Better still, write a generic tree pruner from Listing 7a and add a DELETE command. To insert a subtree, prepare a table of new rows, point its top edge at an existing node as parent, and INSERT it.

Logically, the edge list treewalk is recursive, so how about coding it recursively? Here is a recursive *depth-first* treewalk in PHP on a *mysqli* connection for the `familytree` and `family` tables:

Listing 7b: Recursive edge list subtree in PHP

```
$info = recursivesubtree( $conn, 1, $a = array(), 0 );
foreach( $info as $row )
  echo str_repeat( " ", 2*$row[4] ), ( $row[3] > 0 ) ? "<b>{$row[1]}</b>" : $row[1], "<br/>";

function recursivesubtree( $conn, $rootID, $a, $level ) {
  $childcountqry = "(SELECT COUNT(*) FROM familytree WHERE parentID=t.childID) AS childcount";
  $qry = "SELECT t.childid,f.name,t.parentid,$childcountqry,$level " .
         "FROM familytree t JOIN family f ON t.childID=f.ID " .
         "WHERE parentid=$rootID ORDER BY childcount<>0,t.childID";
  $res = mysqli_query( $conn, $qry );
  while( $row = mysqli_fetch_row( $res )) {
    $a[] = $row;
```

```
    if( $row[3] > 0 ) $a = recursivesubtree( $row[0], $a, $level+1 );  // down before right
  }
  return $a;
}
```

A query, a subquery, a fetch loop and a recursive call—that's all there is to it. A nice feature of this algorithm is that it writes result rows in display-ready order. In MySQL, you must have set recursion depth in *my.cnf/ini* or in your client:

Listing 7c: Recursive edge list subtree

```
SET @@SESSION.max_sp_recursion_depth=25;
DELIMITER go
CREATE PROCEDURE recursivesubtree( iroot INT, ilevel INT )
BEGIN
  DECLARE irows,ichildid,iparentid,ichildcount,done INT DEFAULT 0;
  DECLARE cname VARCHAR(64);
  SET irows = ( SELECT COUNT(*) FROM familytree WHERE parentID=iroot );
  IF ilevel = 0 THEN
    DROP TEMPORARY TABLE IF EXISTS _descendants;
    CREATE TEMPORARY TABLE _descendants (
      childID INT, parentID INT, name VARCHAR(64), childcount INT, level INT
  );
  END IF;
  IF irows > 0 THEN
    BEGIN
      DECLARE cur CURSOR FOR
        SELECT childid,parentid,f.name,
              (SELECT COUNT(*) FROM familytree WHERE parentID=t.childID) AS childcount
        FROM familytree t JOIN family f ON t.childID=f.ID
        WHERE parentid=iroot
        ORDER BY childcount<>0,t.childID;
      DECLARE CONTINUE HANDLER FOR SQLSTATE '02000' SET done = 1;
      OPEN cur;
      WHILE NOT done DO
        FETCH cur INTO ichildid,iparentid,cname,ichildcount;
        IF NOT done THEN
          INSERT INTO _descendants VALUES(ichildid,iparentid,cname,ichildcount,ilevel );
          IF ichildcount > 0 THEN
            CALL recursivesubtree( ichildid, ilevel + 1 );
```

```
          END IF;
        END IF;
      END WHILE;
      CLOSE cur;
    END;
  END IF;
  IF ilevel = 0 THEN   -- Show result table headed by the name that corresponds to iroot:
    SET cname = (SELECT name FROM family WHERE ID=iroot);
    SET @sql = CONCAT('SELECT CONCAT(REPEAT(CHAR(32),2*level),IF(childcount,UPPER(name),name))',
                      ' AS ', CHAR(39),'Descendants of ',cname,CHAR(39),' FROM _descendants');
    PREPARE stmt FROM @sql;
    EXECUTE stmt;
    DROP PREPARE stmt;
  END IF;
END go
DELIMITER ;
CALL recursivesubtree(1,0);
```

```
+-----------------------------------+
| Descendants of Richard Shakespeare |
+-----------------------------------+
| HENRY SHAKESPEARE                 |
|   Joan Shakespeare                |
|   Margaret Shakespeare            |
|   WILLIAM SHAKESPEARE             |
|     SUSANA SHAKESPEARE            |
|       ELIZABETH HALL              |
|         John Bernard              |
|     Hamnet Shakespeare            |
|     JUDITH SHAKESPEARE            |
|       Shakespeare Quiney          |
|       Richard Quiney              |
|       Thomas Quiney               |
|   Gilbert Shakespeare             |
|   JOAN SHAKESPEARE                |
|     William Hart                  |
|     Mary Hart                     |
|     Thomas Hart                   |
```

```
|     Michael Hart                  |
|   Anne Shakespeare                |
|   Richard Shakespeare             |
|   Edmond Shakespeare              |
| John Shakespeare                  |
+-----------------------------------+
```

In MySQL this recursive treewalk can be *100 times slower* than GenericTree()—slower even than Kendall Willet's depth-first algorithm applied to the same tree:

Listing 7d: Depth-first edge list subtree

```
CREATE PROCEDURE depthfirstsubtree( iroot INT )
BEGIN
  DECLARE ilastvisited, inxt, ilastord INT;
  SET ilastvisited = iroot, ilastord = 1;
  DROP TABLE IF EXISTS descendants;
  CREATE TABLE descendants SELECT childID,parentID,-1 AS ord FROM familytree;
  UPDATE descendants SET ord=1 WHERE childID=iroot;
  this: LOOP
    SET inxt = NULL;
    SELECT MIN(childID) INTO inxt FROM descendants   -- go down
    WHERE parentID = ilastvisited AND ord = -1 ;
    IF inxt IS NULL THEN                             -- nothing down, so go right
      SELECT MIN(d2.childID) INTO inxt
      FROM descendants d1
      JOIN descendants d2 ON d1.parentID = d2.parentID AND d1.childID < d2.childID
      WHERE d1.childID = ilastvisited;
    END IF;
    IF inxt IS NULL THEN                             -- nothing right. so go up
      SELECT parentID INTO inxt FROM descendants
      WHERE childID = ilastvisited AND parentID IS NOT NULL;
    END IF;
    UPDATE descendants SET ord = ilastord+1 WHERE childID=inxt AND ord=-1;
    IF ROW_COUNT() > 0 THEN
      SET ilastord = ilastord + 1;
    END IF;
    IF inxt IS NULL THEN
      LEAVE this;
```

```
    END IF;
    SET ilastvisited = inxt;
  END LOOP;
END;
```

One reason for this slowness is that MySQL does not permit multiple references to a temporary table in a query. When all these algorithms are denied temporary tables, though, Willet's algorithm is still slower than the recursive version, and both are far slower than *GenericTree()*.

A simple procedure to retrieve a node's ancestors:

Listing 7e: List a node's ancestors

```
CREATE PROCEDURE ancestors( pid int )
BEGIN
  drop temporary table if exists _ancestors;
  create temporary table _ancestors(parent int);
  set @id = pid;
  repeat
    select parentID,count(*) into @parent,@y from familytree where childID=@id;
    if @y>0 then
      insert into _ancestors values(@parent);
      set @id=@parent;
    end if;
  until @parent is null or @y=0 end repeat;
  select * from _ancestors order by parent;
END;
```

Finally, since MariaDB 10.2.2 and MySQL 8.0.1, a recursive CTE treewalk (see SELECT / WITH in *Chapter 6*): a WITH clause to declare the derived table; a query to initialise that table with the root node; a UNION command; a recursive join; and a final output SELECT. The initialising SELECT creates a root result row that needn't be displayed:

Listing 7f: Walk a tree with a CTE

```
WITH RECURSIVE treewalk AS (
  SELECT
    CAST(1 AS UNSIGNED) AS childID,        -- UNION NEEDS EXACT TYpE MATCH
    CAST(NULL AS UNSIGNED) AS parentID,
    CAST(0 AS UNSIGNED) AS level,
    0 AS siborder
  UNION ALL
```

```
  SELECT familytree.childID, familytree.parentID, treewalk.level+1 AS level, family.siborder
  FROM familytree
  JOIN treewalk ON familytree.parentID=treewalk.childID
  JOIN family   ON family.ID=familytree.childID
)
SELECT
  Concat( Space(level-1), parentID ) AS Parent,
  level-1 AS Depth,
  Group_Concat( childID ORDER BY siborder ) AS Children
FROM treewalk
WHERE level>0
GROUP BY treewalk.parentID ORDER BY treewalk.parentID; -- Unset only_full_group_by sql_mode
+--------+-------+-------------------+
| Parent | Depth | Children          |
+--------+-------+-------------------+
| 1      | 0     | 2,3               |
|  2     | 1     | 4,5,6,7,8,9,10,11 |
|   6    | 2     | 13,12,14          |
|   8    | 2     | 18,15,16,17       |
|    12  | 3     | 19                |
|    14  | 3     | 20,21,22          |
|     19 | 4     | 23                |
+--------+-------+-------------------+
```

The breadth-first logic is that of *Listing 7.*, but the CTE treewalk is about ten times faster. If the graph being traversed is not a tree, *e.g.*, if it is cyclic, avoid an endless loop by changing UNION ALL to UNION DISTINCT.

Edge list tree queries are easier to write, are more flexible, and run faster than their reputation suggests—especially with CTEs. For a tree describing a parts explosion rather than a family, just add columns for weight, quantity, assembly time, cost, price, etc.. Reports need only aggregation and summaries. We will *revisit* this near the end of this chapter.

Enumerating paths in an edge list

Path enumeration in an edge list model of a tree is almost as easy as depth-first subtree traversal:

- create a table for paths,
- seed it with paths of unit length from the tree table,

- iteratively add paths till there are no more to add.

MySQL's INSERT IGNORE command simplifies the code by removing the need for a NOT EXISTS(...) clause in the INSERT ... SELECT statement. Since adjacencies are logically symmetrical, we make path direction the caller's choice, UP or DOWN. But MySQL does impose an astonishing limitation: its TEMPORARY tables can be referenced only once per query!

Listing 8

```
DROP PROCEDURE IF EXISTS ListAdjacencyPaths;
DELIMITER go
CREATE PROCEDURE ListAdjacencyPaths( IN direction CHAR(5) )
BEGIN
  DROP TABLE IF EXISTS paths;
  CREATE TABLE paths(
    start SMALLINT,stop SMALLINT,len SMALLINT,PRIMARY KEY(start,stop)
  ) ENGINE=HEAP;
  IF direction = 'UP' THEN
    INSERT INTO paths SELECT childID,parentID,1 FROM familytree;
  ELSE
    INSERT INTO paths SELECT parentID,childID,1 FROM familytree;
  END IF;
  WHILE ROW_COUNT() > 0 DO
    INSERT IGNORE INTO paths
      SELECT DISTINCT p1.start,p2.stop,p1.len + p2.len
      FROM paths AS p1 INNER JOIN paths AS p2 ON p1.stop = p2.start;
  END WHILE;
  SELECT start, stop, len FROM paths ORDER BY start, stop;
  DROP TABLE paths;
END;
go
DELIMITER ;
```

To find the paths from just one node, seed the paths table with paths from the starting node, then iteratively search a JOIN of familytree and paths for edges which will extend existing paths in the user-specified direction:

Listing 8a

```
DROP PROCEDURE IF EXISTS ListAdjacencyPathsOfNode;
DELIMITER go
CREATE PROCEDURE ListAdjacencyPathsOfNode( IN node SMALLINT, IN direction CHAR(5) )
```

```
BEGIN
  TRUNCATE paths;
  IF direction = 'UP' THEN
    INSERT INTO paths SELECT childID,parentID,1 FROM familytree WHERE childID = node;
  ELSE
    INSERT INTO paths SELECT parentID,childID,1 FROM familytree WHERE parentID = node;
  END IF;
  WHILE ROW_COUNT() > 0 DO
    IF direction = 'UP' THEN
      INSERT IGNORE INTO paths
        SELECT DISTINCT paths.start,familytree.parentID,paths.len + 1
        FROM paths JOIN familytree ON paths.stop = familytree.childID;
    ELSE
      INSERT IGNORE INTO paths
        SELECT DISTINCT paths.start,familytree.childID,paths.len + 1
        FROM paths JOIN familytree ON paths.stop = familytree.parentID;
    END IF;
  END WHILE;
  SELECT start, stop, len FROM paths ORDER BY start, stop;
END;
go
DELIMITER ;
CALL ListAdjacencyPathsOfNode(1,'DOWN');
+-------+------+------+
| start | stop | len  |
+-------+------+------+
|     1 |    2 |    1 |
|     1 |    3 |    1 |
|     1 |    4 |    2 |
|     1 |    5 |    2 |
|     1 |    6 |    2 |
|     1 |    7 |    2 |
|     1 |    8 |    2 |
|     1 |    9 |    2 |
|     1 |   10 |    2 |
|     1 |   11 |    2 |
|     1 |   12 |    3 |
|     1 |   13 |    3 |
```

```
|     1 |   14 |    3 |
|     1 |   15 |    3 |
|     1 |   16 |    3 |
|     1 |   17 |    3 |
|     1 |   18 |    3 |
|     1 |   19 |    4 |
|     1 |   20 |    4 |
|     1 |   21 |    4 |
|     1 |   22 |    4 |
|     1 |   23 |    5 |
+-------+------+------+
```

With CTEs, path queries are far simpler, and they run much faster, *e.g.*, find someone's ancestors:

Listing 8b: List an individual's ancestors (path to root):

```
WITH RECURSIVE ctepath AS (
  SELECT parentID FROM familytree WHERE childID=23            -- PARENT OF CHILDID 23
  UNION ALL
  SELECT f.parentID FROM familytree f                         -- AND THAT INDIVIDUAL'S PARENT ETC
  JOIN ctepath ON f.childID=ctepath.parentID
)
SELECT Group_Concat(parentID) As AncestorsOf23 FROM ctepath;   -- RETURNS 19,12,6,2,1
```

These algorithms don't bend the brain. They perform acceptably with large trees, an order of magnitude faster with CTEs. Querying edge-adjacency lists for subtrees and paths is less daunting than their reputation suggests.

Automate tree drawing!

Scrolling rows of tabular data may be the most boring objects on earth. How to quickly bring them alive? The Google Visualization API library has an *'OrgChart' module* that can make edge list trees look like *Fig 2*, but each instance needs fifty or so lines of specific JavaScript code, plus an additional line of code for each row of data in the tree. Could we autogenerate that code? *Mais oui!* The module needs child node and parent node columns of data, and accepts an optional third column for info that pops up when the mouse hovers. Here is such a query for the Shakespeare family tree:

Listing 9

```
select concat( node.ID,' ', node.name) as node,
       if( edges.parentID is null, '', concat(parent.ID, ' ',parent.name)) as parent,
       if( node.born is null, 'Birthdate unknown', concat( 'Born ', node.born )) as tooltip
```

```
from      family     as node
left join familytree as edges  on node.ID=edges.childID
left join family     as parent on edges.parentID=parent.ID;
```

and here is a PHP function that returns HTML and JavaScript to paint an OrgChart for *any* tree query returning a string node column, a string parent column, and optionally a string tooltip column:

Listing 9a

```
function orgchart( $conn, $qry ) {           /* requires mysqli connection $conn */
  $cols = array(); $rows = array();
  $res = mysqli_query( $conn, $qry ) or exit( mysqli_error($conn) );
  $colcount = mysqli_num_fields( $res );
  if( $colcount < 2 ) exit( "Org chart needs two or three columns" );
  $rowcount = mysqli_num_rows( $res );
  for( $i=0; $i<$colcount; $i++ ) $cols[] = mysqli_fetch_field( $res );
  while( $row = mysqli_fetch_row($res) ) $rows[] = $row;
  echo "<html>\n<head>\n",
       "  <script type='text/javascript' src='https://www.google.com/jsapi'></script>\n",
       "  <script type='text/javascript'>\n",
       "    google.load('visualization', '1', {'packages':['orgchart']});\n",
       "    google.setOnLoadCallback(drawChart);\n",
       "    function drawChart() {\n",
       "      var data = new google.visualization.DataTable();\n";
  for( $i=0; $i<$colcount; $i++ ) echo "      data.addColumn('string','{$cols[$i]->name}')\n";
  echo "      data.addRows([\n";
  for( $j=0; $j<$rowcount; $j++ ) {
    $row = $rows[$j];
    $c = (( $j < $rowcount-1 ) ? "," : "" );
    echo "        ['{$row[0]}','{$row[1]}','{$row[2]}']$c\n";
  }
  echo "      ]);\n",
       "      var chart = new google.visualization.OrgChart(document.getElementById('chart_div'));\n",
       "      var options = {'size':'small','allowHtml':'true','allowCollapse':'true'};\n",
       "      chart.draw(data, options);\n",
       "    }\n",
       "  </script>\n</head>\n<body>\n<div id='chart_div'></div>\n</body>\n</html>";
}
```

Nested sets model of a tree

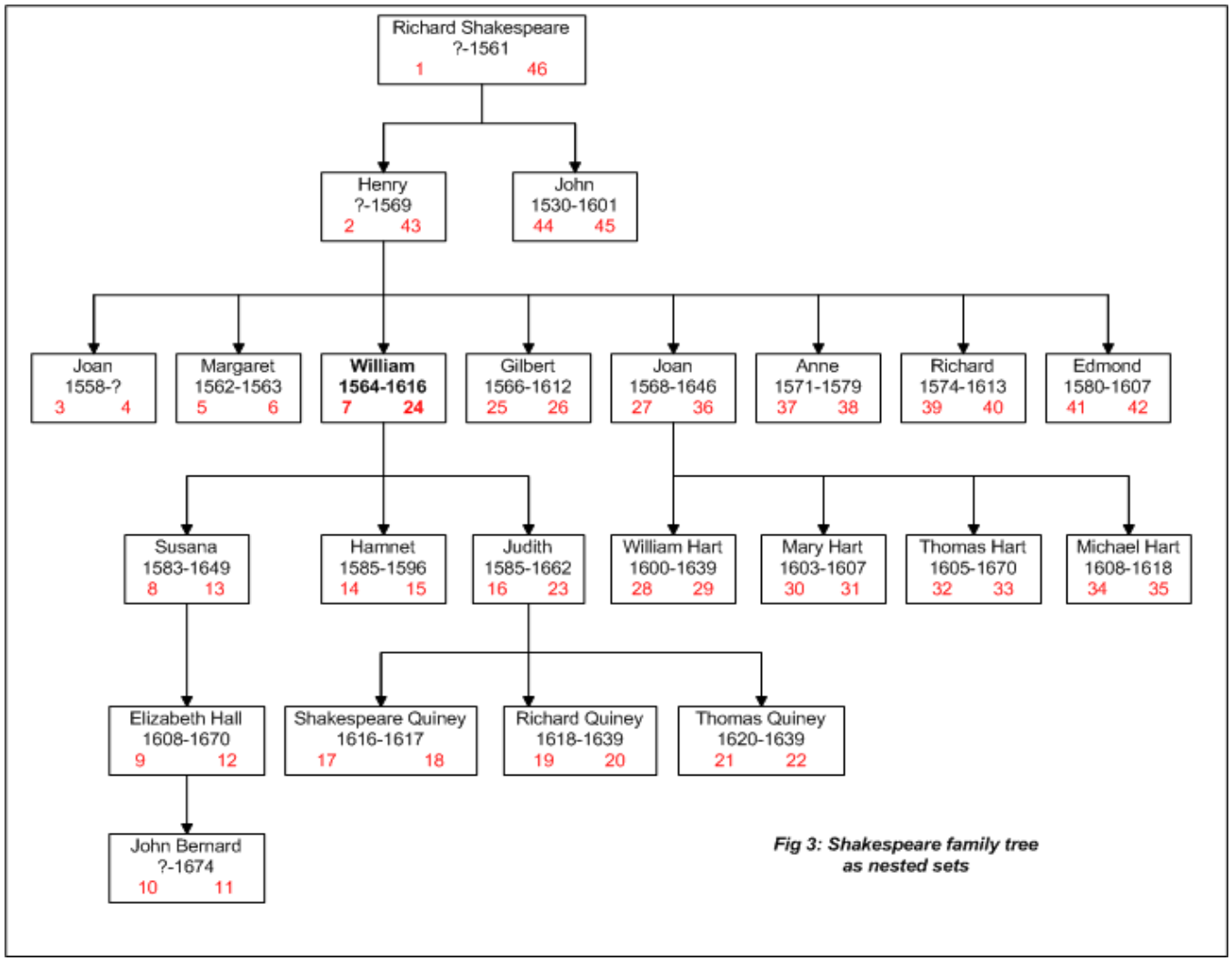


Fig 3: Shakespeare family tree as nested sets

Imagine an oval drawn round every leaf and every subtree in *Fig 2*, and a final oval round the entire tree. The tree is a set. Each subtree is a subset. That is the basic idea of the nested sets model. The advantage of the nested sets model is that root, leaves, subtrees, levels, tree height, ancestors, descendants and paths can be retrieved without recursion or application language code. The disadvantages are:

- initial setup of the tree table can be difficult,
- queries for parents and children are slower and more complicated than with an edge list model,
- insertion, updates and deletion are extremely cumbersome since they may require updates to much of the tree.

The model depends on using a *modified preorder tree traversal* (MPTT) *depth-first* algorithm to assign each node *left* and *right* integers which define the node's tree position. All nodes of a subtree have

- *left* values greater than the subtree parent's *left* value, and
- *right* values smaller than that of the subtree parent's *right* value.

so nested sets queries for subtrees are dead simple. If the numbering scheme is integer-sequential as in Fig 3, the root node receives a *left* value of 1 and a *right* value equal to twice the item count.

To see how to code nested sets using MPTT, trace the ascending integers in Fig 3, starting with 1 on the *left* side of the root node (`Richard Shakespeare`). Following edges downward and leftward, the *left* side of each box gets the next integer.

When you reach a leaf (Joan, *left*=3), the *right* side of that box gets the next integer (4). If there is another node to the right on the same level, continue in that direction; otherwise continue up the *right* side of the subtree you just descended. When you arrive back at the root on the *right* side, you're done. Down, right and up.

A serious problem with this scheme jumps out at you right away: after you've written the Fig 3 tree to a table, what if historians discover an older brother or sister of Henry and John? *Every row in the tree table must be updated!*

Celko and others have proposed alternative numbering schemes to get round this problem, but the logical difficulty remains: inserts and updates can invalidate many or all rows. No SQL CHECK or CONSTRAINT can prevent it. The nested sets model is not good for trees which require frequent updates, and verges on unsupportable for large updatable trees that will be accessed by many concurrent users. But as we'll see, it can be very useful indeed as a tree reporting tool.

Build a nested sets representation from an edge list

Obviously, numbering a tree by hand would be error-prone, seriously impractical for large trees, so it's usually best to code the tree initially as an edge list, then use a stored procedure to translate the edge list representation to nested sets. *Celko*'s depth-first pushdown stack method will translate *any* edge list tree into a nested sets tree, though slowly:

1. Create a result table `nestedsettree`: `node`, `leftedge`, `rightedge`, and a stack pointer (`top`),
2. Seed it with the root node of the edge list, setting `leftedge`=1 and `rightedge` = 2 x (1 + tree size),
3. Initialise a counter `nextedge` to track the next required edge value, i.e. 1+1=2,
4. While that counter is less than the `rightedge` value of the root node ...
    - insert a row for this parent's smallest unwritten child, and drop down a level, or
    - if we're out of children, increment `rightedge`, write it to the current row, and back up a level.

This version handles edge list trees with or without a row containing the root node and its NULL parent:

Listing 10

```
DROP PROCEDURE IF EXISTS EdgeListToNestedSet;
DELIMITER go
CREATE PROCEDURE EdgeListToNestedSet( edgeTable CHAR(64), idCol CHAR(64), parentCol CHAR(64) )
BEGIN
  DECLARE maxrightedge, rows SMALLINT DEFAULT 0;
  DECLARE trees, current SMALLINT DEFAULT 1;
  DECLARE nextedge SMALLINT DEFAULT 2;
  DECLARE msg CHAR(128);
  -- create working tree table as a copy of edgeTable
  DROP TEMPORARY TABLE IF EXISTS tree;
  CREATE TEMPORARY TABLE tree( childID INT, parentID INT );
  SET @sql = CONCAT( 'INSERT INTO tree SELECT ', idCol, ',', parentCol, ' FROM ', edgeTable );
  PREPARE stmt FROM @sql; EXECUTE stmt; DROP PREPARE stmt;
  -- initialise result table
  DROP TABLE IF EXISTS nestedsettree;
  CREATE TABLE nestedsettree (
    top SMALLINT, nodeID SMALLINT, leftedge SMALLINT, rightedge SMALLINT,
    KEY(nodeID,leftedge,rightedge)
  ) ENGINE=HEAP;
  -- root is child with NULL parent or parent which is not a child
```

```
SET @nulls = ( SELECT Count(*) FROM tree WHERE parentID IS NULL );
IF @nulls>1 THEN SET trees=2;
ELSEIF @nulls=1 THEN
  SET @root = ( SELECT childID FROM tree WHERE parentID IS NULL );
  DELETE FROM tree WHERE childID=@root;
ELSE
  SET @sql = CONCAT( 'SELECT Count(DISTINCT f.', parentcol, ') INTO @roots FROM ', edgeTable,
                     ' f LEFT JOIN ', edgeTable, ' t ON f.', parentCol, '=', 't.', idCol,
                     ' WHERE t.', idCol, ' IS NULL' );
  PREPARE stmt FROM @sql; EXECUTE stmt; DROP PREPARE stmt;
  IF @roots <> 1 THEN SET trees=@roots;
  ELSE
    SET @sql = CONCAT( 'SELECT DISTINCT f.', parentCol, ' INTO @root FROM ', edgeTable,
                       ' f LEFT JOIN ', edgeTable, ' t ON f.', parentCol, '=', 't.',
                      idCol, ' WHERE t.', idCol, ' IS NULL' );
    PREPARE stmt FROM @sql; EXECUTE stmt; DROP PREPARE stmt;
  END IF;
END IF;
IF trees<>1 THEN
  SET msg=IF(trees=0,"No tree found", "Table has multiple trees" );
  SELECT msg AS 'Cannot continue';
ELSE    -- build nested sets tree
  SET maxrightedge = 2 * (1 + (SELECT COUNT(*) FROM tree));
  INSERT INTO nestedsettree VALUES( 1, @root, 1, maxrightedge );
  WHILE nextedge < maxrightedge DO
    SET rows=(SELECT Count(*) FROM nestedsettree s JOIN tree t ON s.nodeID=t.parentID AND s.top=current);
    IF rows > 0 THEN
      BEGIN
        INSERT INTO nestedsettree
          SELECT current+1, MIN(t.childID), nextedge, NULL
          FROM nestedsettree AS s
          JOIN tree AS t ON s.nodeID = t.parentID AND s.top = current;
        DELETE FROM tree
        WHERE childID = (SELECT nodeID FROM nestedsettree WHERE top=(current+1));
        SET nextedge = nextedge + 1, current = current + 1;
       END;
     ELSE
       UPDATE nestedsettree SET rightedge=nextedge, top = -top WHERE top=current;
```

```
        SET nextedge=nextedge+1, current=current-1;
      END IF;
    END WHILE;
    -- show result
    IF (SELECT COUNT(*) FROM tree) > 0 THEN
      SELECT 'Orphaned rows remain';
    END IF;
    DROP TEMPORARY TABLE tree;
  END IF;
END;
go
DELIMITER ;
CALL EdgeListToNestedSet( 'familytree', 'childID', 'parentID', 1, 0 );
SELECT
  nodeID, PersonName(nodeID) AS Name,
  ABS(top) AS 'Tree Level', leftedge AS 'Left', rightedge AS 'Right'
FROM nestedsettree
ORDER BY nodeID;
+--------+----------------------+------------+------+-------+
| nodeID | Name                 | Tree Level | Left | Right |
+--------+----------------------+------------+------+-------+
|      1 | Richard Shakespeare  |          1 |    1 |    46 |
|      2 | Henry Shakespeare    |          2 |    2 |    43 |
|      3 | John Shakespeare     |          2 |   44 |    45 |
|      4 | Joan Shakespeare     |          3 |    3 |     4 |
|      5 | Margaret Shakespeare |          3 |    5 |     6 |
|      6 | William Shakespeare  |          3 |    7 |    24 |
|      7 | Gilbert Shakespeare  |          3 |   25 |    26 |
|      8 | Joan Shakespeare     |          3 |   27 |    36 |
|      9 | Anne Shakespeare     |          3 |   37 |    38 |
|     10 | Richard Shakespeare  |          3 |   39 |    40 |
|     11 | Edmond Shakespeare   |          3 |   41 |    42 |
|     12 | Susana Shakespeare   |          4 |    8 |    13 |
|     13 | Hamnet Shakespeare   |          4 |   14 |    15 |
|     14 | Judith Shakespeare   |          4 |   16 |    23 |
|     15 | William Hart         |          4 |   28 |    29 |
|     16 | Mary Hart            |          4 |   30 |    31 |
|     17 | Thomas Hart          |          4 |   32 |    33 |
```

```
|     18 | Michael Hart         |          4 |   34 |    35 |
|     19 | Elizabeth Hall       |          5 |    9 |    12 |
|     20 | Shakespeare Quiney   |          5 |   17 |    18 |
|     21 | Richard Quiney       |          5 |   19 |    20 |
|     22 | Thomas Quiney        |          5 |   21 |    22 |
|     23 | John Bernard         |          6 |   10 |    11 |
+--------+----------------------+------------+------+-------+
```

Verify the function with a query that generates an edge list tree from a nested sets tree:

Listing 10a:

```
SELECT a.nodeID, b.nodeID AS parent
FROM nestedsettree AS a
LEFT JOIN nestedsettree AS b ON b.leftedge = (
  SELECT MAX( leftedge )
  FROM nestedsettree AS t
  WHERE a.leftedge > t.leftedge AND a.leftedge < t.rightedge
)
ORDER BY a.nodeID;
```

For how to keep multiple trees in one table, see "Multiple trees in one table" on our *Queries page*.

Finding a node's parent and children

In an edge list, a node's parent is the parentID, and its children are the rows where that nodeID is parentID. In contrast, nested sets queries for parents and their children are tortuous and slow. One way to fetch the child nodes of a given row is to INNER JOIN the nested sets table `AS parent` to itself `AS child ON child.leftedge BETWEEN parent.leftedge AND parent.rightedge`, then scope on the target row's `leftedge` and `rightedge` values. In the resulting list, `child.nodeID` values one level down occur once and are children, grandkids are two levels down and occur twice, and so on:

Listing 11

```
SELECT PersonName(child.nodeID) AS 'Descendants of William', COUNT(*) AS Generation
FROM nestedsettree AS parent
JOIN nestedsettree AS child ON child.leftedge BETWEEN parent.leftedge AND parent.rightedge
WHERE parent.leftedge > 7 AND parent.rightedge < 24       -- William's leftedge, rightedge
GROUP BY child.nodeID;
```

```
+------------------------+------------+
| Descendants of William | Generation |
+------------------------+------------+
| Susana Shakespeare     |          1 |
| Hamnet Shakespeare     |          1 |
| Judith Shakespeare     |          1 |
| Elizabeth Hall         |          2 |
| Shakespeare Quiney     |          2 |
| Richard Quiney         |          2 |
| Thomas Quiney          |          2 |
| John Bernard           |          3 |
+------------------------+------------+
```

Then `HAVING COUNT(child.nodeID)=1` scopes retrieved rows to children:

Listing 11a

```
SELECT PersonName(child.nodeID) AS 'Children of William'
FROM nestedsettree AS parent
JOIN nestedsettree AS child ON child.leftedge BETWEEN parent.leftedge AND parent.rightedge
WHERE parent.leftedge > 7 AND parent.rightedge < 24
GROUP BY child.nodeID
HAVING COUNT(child.nodeID)=1
+---------------------+
| Children of William |
+---------------------+
| Susana Shakespeare  |
| Hamnet Shakespeare  |
| Judith Shakespeare  |
+---------------------+
```

Retrieving a subtree or a subset of parents requires yet another join:

Listing 11b

```
SELECT Parent, Group_Concat(Child ORDER BY Child) AS Children
FROM (
  SELECT master.nodeID AS Parent, child.nodeID AS Child
  FROM nestedsettree AS master
  JOIN nestedsettree AS parent
  JOIN nestedsettree AS child ON child.leftedge BETWEEN parent.leftedge AND parent.rightedge
```

```
  WHERE parent.leftedge > master.leftedge AND parent.rightedge < master.rightedge
  GROUP BY master.nodeID, child.nodeID
  HAVING COUNT(*)=1 ) AS tmp
WHERE parent in(6,8,12,14)
GROUP BY Parent;
+--------+-------------------+
| Parent | Children          |
+--------+-------------------+
|      6 | 12,13,14          |
|      8 | 15,16,17,18       |
|     12 | 19                |
|     14 | 20,21,22          |
+--------+-------------------+
```

This takes *hundreds* of times longer than a query for the same info from an edge list! An aggregating version of *Listing 19* is easier to write, but is an even worse performer:

Listing 11c

```
SELECT p.nodeID AS Parent, Group_Concat(c.nodeID) AS Children
FROM nestedsettree AS p
JOIN nestedsettree AS c
  ON p.leftedge = (SELECT MAX(s.leftedge) FROM nestedsettree AS s
                   WHERE c.leftedge > s.leftedge AND c.leftedge < s.rightedge)
GROUP BY Parent;
```

Logic which is reciprocal to that of Listing 11a gets us the parent of a node:

1. retrieve its `leftedge` and `rightedge` values,
2. compute its level,
3. find the node that is one level up and has edge values outside this node's `leftedge` and `rightedge` values.

Listing 12

```
DROP PROCEDURE IF EXISTS ShowNestedSetParent;
DELIMITER go
CREATE PROCEDURE ShowNestedSetParent( node SMALLINT )
BEGIN
  DECLARE level, thisleft, thisright SMALLINT DEFAULT 0;
  -- find node edges
  SELECT leftedge, rightedge INTO thisleft, thisright
```

```
  FROM nestedsettree
  WHERE nodeID = node;
  -- find node level
  SELECT COUNT(parent.nodeid) INTO level
  FROM nestedsettree AS parent
    JOIN nestedsettree AS child ON child.leftedge BETWEEN parent.leftedge AND parent.rightedge
  WHERE child.nodeid = node
  GROUP BY child.nodeid;
  -- find parent
  SELECT PersonName(n2.nodeid) AS Parent
  FROM nestedsettree AS n1
    JOIN nestedsettree AS n2 ON n2.leftedge BETWEEN n1.leftedge AND n1.rightedge
  WHERE n2.leftedge < 7 AND n2.rightedge > 24
  GROUP BY n2.nodeid
  HAVING COUNT(n2.nodeid) = level-1;
END;
go
DELIMITER ;
CALL ShowNestedSetParent(6);
+-------------------+
| Parent            |
+-------------------+
| Henry Shakespeare |
+-------------------+
```

Other queries

For some query problems, edge list and nested sets queries are equivalently simple. For example, to find the tree root and leaves, compare *Listing 6* with:

Listing 13

```
SELECT
  name AS Paterfamilias,
  IFNULL(born,'?') AS Born,
  IFNULL(died,'?') AS Died
FROM nestedsettree AS t
INNER JOIN family AS f ON t.nodeID=f.ID
```

```
WHERE leftedge = 1;
+---------------------+------+------+
| Paterfamilias       | Born | Died |
+---------------------+------+------+
| Richard Shakespeare | ?    | 1561 |
+---------------------+------+------+
SELECT
  name AS 'Childless Shakespeares',
  IFNULL(born,'?') AS Born,
  IFNULL(died,'?') AS Died
FROM nestedsettree AS t
INNER JOIN family AS f ON t.nodeID=f.ID
WHERE rightedge = leftedge + 1;
+------------------------+------+------+
| Childless Shakespeares | Born | Died |
+------------------------+------+------+
| Joan Shakespeare       | 1558 | ?    |
| Margaret Shakespeare   | 1562 | 1563 |
| John Bernard           | ?    | 1674 |
| Hamnet Shakespeare     | 1585 | 1596 |
| Shakespeare Quiney     | 1616 | 1617 |
| Richard Quiney         | 1618 | 1639 |
| Thomas Quiney          | 1620 | 1639 |
| Gilbert Shakespeare    | 1566 | 1612 |
| William Hart           | 1600 | 1639 |
| Mary Hart              | 1603 | 1607 |
| Thomas Hart            | 1605 | 1670 |
| Michael Hart           | 1608 | 1618 |
| Anne Shakespeare       | 1571 | 1579 |
| Richard Shakespeare    | 1574 | 1613 |
| Edmond Shakespeare     | 1580 | 1607 |
| John Shakespeare       | 1530 | 1601 |
+------------------------+------+------+
```

As we saw in Listings *11* and 11a, finding subtrees in a nested sets model requires no stored procedure. To retrieve descendants of William, just ask for the nodes whose `leftedge` values are greater, and whose `rightedge` values are smaller than William's:

Listing 14

```
SELECT PersonName(t.nodeID) AS Descendant
FROM nestedsettree AS s
JOIN nestedsettree AS t ON s.leftedge < t.leftedge AND s.rightedge > t.rightedge
JOIN family f ON s.nodeID = f.ID
WHERE f.name = 'William Shakespeare';
```

Finding a single path in the nested sets model is about as complicated as edge list path enumeration (Listings *8*, *9*):

Listing 15

```
SELECT
  t2.nodeID AS Node,
  PersonName(t2.nodeID) AS Person,
  (SELECT COUNT(*)
   FROM nestedsettree AS t4
   WHERE t4.leftedge BETWEEN t1.leftedge AND t1.rightedge
     AND t2.leftedge BETWEEN t4.leftedge AND t4.rightedge
   ) AS Path
FROM nestedsettree AS t1
  JOIN nestedsettree AS t2 ON t2.leftedge BETWEEN t1.leftedge AND t1.rightedge
  JOIN nestedsettree AS t3 ON t3.leftedge BETWEEN t2.leftedge AND t2.rightedge
WHERE t1.nodeID=(SELECT ID FROM family WHERE name='William Shakespeare')
  AND t3.nodeID=(SELECT ID FROM family WHERE name='John Bernard');
+------+---------------------+------+
| Node | Person              | Path |
+------+---------------------+------+
|    6 | William Shakespeare |    1 |
|   12 | Susana Shakespeare  |    2 |
|   19 | Elizabeth Hall      |    3 |
|   23 | John Bernard        |    4 |
+------+---------------------+------+
```

Displaying the tree

Here the nested sets model shines. The arithmetic that built the tree makes short work of summary queries. For example to retrieve a node list which preserves all parent-child relations, we need just two facts:

- listing order is the order taken in the node walk that created the tree, i.e. `leftedge`,
- a node's indentation depth is simply the JOIN (edge) count from root to node:

Listing 16

```
SELECT
  CONCAT( SPACE(2*COUNT(parent.nodeid)-2), PersonName(child.nodeid) ) AS 'The Shakespeare Family Tree'
FROM nestedsettree AS parent
  INNER JOIN nestedsettree AS child
  ON child.leftedge BETWEEN parent.leftedge AND parent.rightedge
GROUP BY child.nodeid
ORDER BY child.leftedge;
+----------------------------+
| The Shakespeare Family Tree |
+----------------------------+
| Richard Shakespeare        |
|   Henry Shakespeare        |
|     Joan Shakespeare       |
|     Margaret Shakespeare   |
|     William Shakespeare    |
|       Susana Shakespeare   |
|         Elizabeth Hall     |
|           John Bernard     |
|       Hamnet Shakespeare   |
|       Judith Shakespeare   |
|         Shakespeare Quiney |
|         Richard Quiney     |
|         Thomas Quiney      |
|     Gilbert Shakespeare    |
|     Joan Shakespeare       |
|       William Hart         |
|       Mary Hart            |
|       Thomas Hart          |
|       Michael Hart         |
|     Anne Shakespeare       |
|     Richard Shakespeare    |
|     Edmond Shakespeare     |
|   John Shakespeare         |
+----------------------------+
```

To retrieve only a subtree, add a query clause which restricts nodes to those whose edges are within the range of the parent node's left and right edge values, for example for William and his descendants...

```
WHERE n1.leftedge >= 7 AND n1.rightedge <=24
```

Node insertions, updates and deletions

Nested set arithmetic also helps with insertions, updates and deletions, but the problem remains that changing just one node can require changing much of the tree.

Inserting a node in the tree requires at least two pieces of information: the `nodeID` to insert, and the `nodeID` of its parent. The model is normalised so the `nodeID` first must have been added to the parent (`family`) table. The algorithm for adding the node to the tree is:

1. increment `leftedge` by 2 in nodes where the `rightedge` value is greater than the parent's `rightedge`,
2. increment `rightedge` by 2 in nodes where the `leftedge` value is greater than the parent's `leftedge`,
3. insert a row with the given `nodeID`, `leftedge` = 1 + parent's `leftedge`, `rightedge` = 2 + parent's `leftedge`.

That's not difficult, but *all* rows will have to be updated!

Listing 17

```
DROP PROCEDURE IF EXISTS InsertNestedSetNode;
DELIMITER go
CREATE PROCEDURE InsertNestedSetNode( IN node SMALLINT, IN parent SMALLINT )
BEGIN
  DECLARE parentleft, parentright SMALLINT DEFAULT 0;
  SELECT leftedge, rightedge
    INTO parentleft, parentright
  FROM nestedsettree
  WHERE nodeID = parent;
  IF FOUND_ROWS() = 1 THEN
    BEGIN
      UPDATE nestedsettree
        SET rightedge = rightedge + 2
```

```
      WHERE rightedge > parentleft;
      UPDATE nestedsettree
        SET leftedge = leftedge + 2
      WHERE leftedge > parentleft;
      INSERT INTO nestedsettree
        VALUES ( 0, node, parentleft + 1, parentleft + 2 );
    END;
  END IF;
END;
go
DELIMITER ;
```

"Sibline" or horizontal order is obviously significant in family trees, but may not be significant in other trees. Listing 17 adds the new node at the left edge of the sibline. To specify another position, modify the procedure to accept a third parameter for the `nodeID` which is to be to the left or right of the insertion point.

Updating a node in place requires nothing more than editing `nodeID` to point at a different parent row.

Deleting a node raises the problem of how to repair links severed by the deletion. In tree models of parts explosions, the item to be deleted is often replaced by a new item, so it can be treated like a simple node update. In organisational boss-employee charts, though, does a colleague move over, does a subordinate get promoted, does everybody in the subtree move up a level, or does something else happen? No formula can catch all the possibilities. Listing 18 illustrates how to handle two common scenarios, move everyone up, and move someone over. All possibilities except simple node replacement involve changes elsewhere in the tree.

Listing 18

```
DROP PROCEDURE IF EXISTS DeleteNestedSetNode;
DELIMITER go
CREATE PROCEDURE DeleteNestedSetNode( IN mode CHAR(7), IN node SMALLINT )
BEGIN
  DECLARE thisleft, thisright SMALLINT DEFAULT 0;
  SELECT leftedge, rightedge
    INTO thisleft, thisright
  FROM nestedsettree
  WHERE nodeID = node;
  IF mode = 'PROMOTE' THEN
```

```
    BEGIN                                                          -- Ian Holsman found these bugs
      DELETE FROM nestedsettree
      WHERE nodeID = node;
        UPDATE nestedsettree
        SET leftedge = leftedge - 1, rightedge = rightedge - 1     -- not = thisleft
      WHERE leftedge BETWEEN thisleft AND thisright;
      UPDATE nestedsettree
        SET rightedge = rightedge - 2
      WHERE rightedge > thisright;
      UPDATE nestedsettree
        SET leftedge = leftedge - 2
      WHERE leftedge > thisright;                                  -- not > thisleft
    END;
  ELSEIF mode = 'REPLACE' THEN
    BEGIN
      UPDATE nestedsettree
        SET leftedge = thisleft - 1, rightedge = thisright
      WHERE leftedge = thisleft + 1;
      UPDATE nestedsettree
        SET rightedge = rightedge - 2
      WHERE rightedge > thisleft;
      UPDATE nestedsettree
        SET leftedge = leftedge - 2
      WHERE leftedge > thisleft;
      DELETE FROM nestedsettree
      WHERE nodeID = node;
    END;
  END IF;
END;
go
DELIMITER ;
```

Nested set model summary

Some nested sets queries are quicker than some edge list counterparts. Some are slower. None are faster than edge list queries using recursive CTEs. Given the concurrency nightmare that nested sets impose for inserts and deletions, the

nested sets model is probably best reserved for use with static trees where CTE's aren't available and queries mostly aim at subtrees.

If you will be using the nested sets model, you may be converting back and forth with edge list models, so here is a simple query to build an edge list from a nested sets tree:

Listing 19

```
SELECT p.nodeID AS parentID, c.nodeID AS childID
FROM nestedsettree AS p
JOIN nestedsettree AS c
  ON p.leftedge = (SELECT MAX(s.leftedge) FROM nestedsettree AS s
                   WHERE c.leftedge > s.leftedge AND c.leftedge < s.rightedge)
ORDER BY p.nodeID;
```

Edge list model of a non-tree graph

Many graphs are not trees. Imagine a small airline which has just acquired licences for flights no longer than 6,000 km between Los Angeles (LAX), New York (JFK), Heathrow in London, Charles de Gaulle in Paris, Amsterdam-Schiphol, Arlanda in Sweden, and Helsinki-Vantaa. You have been asked to compute the shortest possible one-way routes that do not deviate more than 90° from the direction of the first hop—roughly, one-way routes and no circuits.

Airports are *nodes*, flights are *edges*, routes are *paths*. We will need three tables.

Airports (nodes)

To identify an airport we need its code, location name, latitude and longitude. Latitude and longitude are usually given as degrees, minutes and seconds, north or south of the equator, east or west of Greenwich. To hide details that aren't directly relevant to nodes and edges, code latitude and longitude as simple reals where longitudes west of Greenwich and latitudes south of the equator are negative, whilst longitudes east of Greenwich and latitudes north of the equator are positive:

Listing 20

```
CREATE TABLE airports (
  code char(3) NOT NULL,
```

```
  city char(100) default NULL,
  latitude float NOT NULL,
  longitude float NOT NULL,
  PRIMARY KEY (code)
) ;

INSERT INTO airports VALUES ('JFK', 'New York, NY', 40.75, -73.97);
INSERT INTO airports VALUES ('LAX', 'Los Angeles, CA', 34.05, -118.22);
INSERT INTO airports VALUES ('LHR', 'London, England', 51.5, -0.45);
INSERT INTO airports VALUES ('HEL', 'Helsinki, Finland', 60.17, 24.97);
INSERT INTO airports VALUES ('CDG', 'Paris, France', 48.86, 2.33);
INSERT INTO airports VALUES ('STL', 'St Louis, MO', 38.63, -90.2);
INSERT INTO airports VALUES ('ARN', 'Stockholm, Sweden', 59.33, 18.05);
```

Flights (edges)

The model attaches two weights to flights: *distance* and *direction*.

We need a method of calculating the Great Circle Distance—the geographical distance between any two cities - another natural job for a stored function. The distance calculation

- converts to radians the degree coordinates of any two points on the earth's surface,
- calculates the angle of the arc subtended by the two points, and
- converts the result, also in radians, to surface (circumferential) kilometres (1 radian=6,378.388 km).

Listing 21

```
SET GLOBAL log_bin_trust_function_creators=TRUE;   -- since 5.0.16
DROP FUNCTION IF EXISTS GeoDistKM;
DELIMITER go
CREATE FUNCTION GeoDistKM( lat1 FLOAT, lon1 FLOAT, lat2 FLOAT, lon2 FLOAT ) RETURNS float
BEGIN
  DECLARE pi, q1, q2, q3 FLOAT;
  SET pi = PI();
  SET lat1 = lat1 * pi / 180;
  SET lon1 = lon1 * pi / 180;
  SET lat2 = lat2 * pi / 180;
```

```
  SET lon2 = lon2 * pi / 180;
  SET q1 = COS(lon1-lon2);
  SET q2 = COS(lat1-lat2);
  SET q3 = COS(lat1+lat2);
  SET rads = ACOS( 0.5*((1.0+q1)*q2 - (1.0-q1)*q3) );
  RETURN 6378.388 * rads;
END;
go
DELIMITER ;
```

That takes care of flight distances. Flight direction is, approximately, the arctangent (ATAN) of the difference between `flights.depart` and `flights.arrive` latitudes and longitudes. Now we can seed the airline's `flights` table with one-hop flights up to 6,000 km long:

Listing 22

```
CREATE TABLE flights (
  id INT PRIMARY KEY AUTO_INCREMENT,
  depart CHAR(3),
  arrive CHAR(3),
  distance DECIMAL(10,2),
  direction DECIMAL(10,2)
);

INSERT INTO flights
  SELECT
    NULL,
    depart.code,
    arrive.code,
    ROUND(GeoDistKM(depart.latitude,depart.longitude,arrive.latitude,arrive.longitude),2),
    ROUND(DEGREES(ATAN(arrive.latitude-depart.latitude,arrive.longitude-depart.longitude)),2)
  FROM airports AS depart
  INNER JOIN airports AS arrive ON depart.code <> arrive.code
  HAVING Km <= 6000;

SELECT * FROM flights;
+----+--------+--------+----------+-----------+
| id | depart | arrive | distance | direction |
+----+--------+--------+----------+-----------+
```

```
|  1 | LAX    | JFK    | 3941.18  | 8.61      |
|  2 | LHR    | JFK    | 5550.77  | -171.68   |
|  3 | CDG    | JFK    | 5837.46  | -173.93   |
|  4 | STL    | JFK    | 1408.11  | 7.44      |
|  5 | JFK    | LAX    | 3941.18  | -171.39   |
|  6 | STL    | LAX    | 2553.37  | -170.72   |
|  7 | JFK    | LHR    | 5550.77  | 8.32      |
|  8 | HEL    | LHR    | 1841.91  | -161.17   |
|  9 | CDG    | LHR    | 354.41   | 136.48    |
| 10 | ARN    | LHR    | 1450.12  | -157.06   |
| 11 | LHR    | HEL    | 1841.91  | 18.83     |
| 12 | CDG    | HEL    | 1912.96  | 26.54     |
| 13 | ARN    | HEL    | 398.99   | 6.92      |
| 14 | JFK    | CDG    | 5837.46  | 6.07      |
| 15 | LHR    | CDG    | 354.41   | -43.52    |
| 16 | HEL    | CDG    | 1912.96  | -153.46   |
| 17 | ARN    | CDG    | 1545.23  | -146.34   |
| 18 | JFK    | STL    | 1408.11  | -172.56   |
| 19 | LAX    | STL    | 2553.37  | 9.28      |
| 20 | LHR    | ARN    | 1450.12  | 22.94     |
| 21 | HEL    | ARN    | 398.99   | -173.08   |
| 22 | CDG    | ARN    | 1545.23  | 33.66     |
+----+--------+--------+----------+-----------+
```

The distances agree approximately with public information sources for flight lengths. For a pair of airports A and B not very near the poles, the error in calculating direction using ATAN(), is small. To remove that error, use a formula from spherical trigonometry (for example at *http://www.boeing-727.com/Data/fly%20odds/distance.html*) instead of ATAN().

Routes (paths)

A route is a *path* along one or more of these *edges*, so `flights:routes` is a 1:many relationship. For simplicity, though, it's efficient to denormalise representation of routes with a variation of the *materialised path model* to store all the hops of one route as a list of flights in one `routes` column. The column `routes.route` is the sequence of airports, from first

departure to final arrival, the column `routes.hops` is the number of hops in that route, and the column `routes.direction` is the direction:

Listing 23

```
CREATE TABLE routes (
  id INT PRIMARY KEY AUTO_INCREMENT,
  depart CHAR(3),
  arrive CHAR(3),
  hops SMALLINT,
  route CHAR(50),
  distance DECIMAL(10,2),
  direction DECIMAL(10,2)
);
```

Starting with an empty `routes` table, how do we populate it with the shortest `routes` between all ordered pairs of `airports`?

1. Insert all 1-hop flights from the `flights` table.
2. Add in the set of shortest multi-hop routes for all pairs of airports which don't have rows in the flights table.

For 1-hop flights we just write:

Listing 24

```
INSERT INTO routes
  SELECT NULL,depart,arrive,1,CONCAT(depart,',',arrive),distance,direction
  FROM flights;
```

NULL is a placeholder for the auto-incrementing `id` column.

For multi-hop routes, iteratively add in sets of all allowed 2-hop, 3-hop, ... n-hop routes, replacing longer routes by shorter routes as we find them, until there is nothing more to add or replace. That also decpmposes to two logical steps: add hops to build the set of next allowed routes, and update longer routes with shorter ones.

Next allowed routes

The set of next allowed routes is the set of shortest routes that can be built by adding, to existing routes, flights that leave from the last arrival airport of an existing route, arrive at an airport not yet in the given route, and stay within ± 90° of the route's initial compass direction. So every new route is a JOIN between `routes` and `flights` where ...

- `depart = routes.depart,`
- `arrive = flights.arrive,`
- `flights.depart = routes.arrive,`
- `distance = MIN(routes.distance + flights.distance),`
- `LOCATE( flights.arrive,routes.route) = 0,`
- `flights.direction+360 > routes.direction+270 AND flights.direction+360 < routes.direction+450`

This looks like a natural logical unit of work for a View:

Listing 25

```
CREATE OR REPLACE VIEW nextroutes AS
  SELECT
    routes.depart, flights.arrive, routes.hops+1 AS hops,
    CONCAT(routes.route, ',', flights.arrive) AS route,
    MIN(routes.distance + flights.distance) AS distance, routes.direction
  FROM routes
  JOIN flights ON routes.arrive = flights.depart AND LOCATE(flights.arrive,routes.route) = 0
  WHERE flights.direction BETWEEN routes.direction-90 AND routes.direction+90
  GROUP BY depart,arrive;
```

How to add these new hops to `routes`? In standard SQL, this variant on a query by Scott Stephens should do it...

Listing 26

```
INSERT INTO routes
  SELECT NULL,depart,arrive,hops,route,distance,direction FROM nextroutes
  WHERE (nextroutes.depart,nextroutes.arrive) NOT IN (
    SELECT depart,arrive FROM routes
  );
```

but MySQL does not yet support subqueries on the update table. No worries, rewriting the subquery as a join speeds it up:

Listing 27

```
INSERT INTO routes
  SELECT NULL, nextroutes.depart, nextroutes.arrive, nextroutes.hops,
         nextroutes.route, nextroutes.distance, nextroutes.direction
  FROM nextroutes
  LEFT JOIN routes ON nextroutes.depart = routes.depart AND nextroutes.arrive = routes.arrive
  WHERE routes.ID IS NULL;
```

Running that code right after the initial seeding from `flights` gives ...

```
SELECT * FROM routes;
+----+--------+--------+------+-------------+----------+-----------+
| id | depart | arrive | hops | route       | distance | direction |
+----+--------+--------+------+-------------+----------+-----------+
|  1 | LAX    | JFK    |    1 | LAX,JFK     | 3941.18  | 8.61      |
|  2 | LHR    | JFK    |    1 | LHR,JFK     | 5550.77  | -171.68   |
|  3 | CDG    | JFK    |    1 | CDG,JFK     | 5837.46  | -173.93   |
|  4 | STL    | JFK    |    1 | STL,JFK     | 1408.11  | 7.44      |
|  5 | JFK    | LAX    |    1 | JFK,LAX     | 3941.18  | -171.39   |
|  6 | STL    | LAX    |    1 | STL,LAX     | 2553.37  | -170.72   |
|  7 | JFK    | LHR    |    1 | JFK,LHR     | 5550.77  | 8.32      |
|  8 | HEL    | LHR    |    1 | HEL,LHR     | 1841.91  | -161.17   |
|  9 | CDG    | LHR    |    1 | CDG,LHR     | 354.41   | 136.48    |
| 10 | ARN    | LHR    |    1 | ARN,LHR     | 1450.12  | -157.06   |
| 11 | LHR    | HEL    |    1 | LHR,HEL     | 1841.91  | 18.83     |
| 12 | CDG    | HEL    |    1 | CDG,HEL     | 1912.96  | 26.54     |
| 13 | ARN    | HEL    |    1 | ARN,HEL     | 398.99   | 6.92      |
| 14 | JFK    | CDG    |    1 | JFK,CDG     | 5837.46  | 6.07      |
| 15 | LHR    | CDG    |    1 | LHR,CDG     | 354.41   | -43.52    |
| 16 | HEL    | CDG    |    1 | HEL,CDG     | 1912.96  | -153.46   |
| 17 | ARN    | CDG    |    1 | ARN,CDG     | 1545.23  | -146.34   |
| 18 | JFK    | STL    |    1 | JFK,STL     | 1408.11  | -172.56   |
| 19 | LAX    | STL    |    1 | LAX,STL     | 2553.37  | 9.28      |
| 20 | LHR    | ARN    |    1 | LHR,ARN     | 1450.12  | 22.94     |
| 21 | HEL    | ARN    |    1 | HEL,ARN     | 398.99   | -173.08   |
| 22 | CDG    | ARN    |    1 | CDG,ARN     | 1545.23  | 33.66     |
| 23 | ARN    | JFK    |    2 | ARN,LHR,JFK | 7000.89  | -157.06   |
| 24 | CDG    | LAX    |    2 | CDG,JFK,LAX | 9778.64  | -173.93   |
```

```
| 25 | CDG    | STL    |    2 | CDG,JFK,STL | 7245.57  | -173.93   |
| 26 | HEL    | JFK    |    2 | HEL,LHR,JFK | 7392.68  | -161.17   |
| 27 | JFK    | ARN    |    2 | JFK,LHR,ARN | 7000.89  | 8.32      |
| 28 | JFK    | HEL    |    2 | JFK,LHR,HEL | 7392.68  | 8.32      |
| 29 | LAX    | CDG    |    2 | LAX,JFK,CDG | 9778.64  | 8.61      |
| 30 | LAX    | LHR    |    2 | LAX,JFK,LHR | 9491.95  | 8.61      |
| 31 | LHR    | LAX    |    2 | LHR,JFK,LAX | 9491.95  | -171.68   |
| 32 | LHR    | STL    |    2 | LHR,JFK,STL | 6958.88  | -171.68   |
| 33 | STL    | CDG    |    2 | STL,JFK,CDG | 7245.57  | 7.44      |
| 34 | STL    | LHR    |    2 | STL,JFK,LHR | 6958.88  | 7.44      |
+----+--------+--------+------+-------------+----------+-----------+
```

... adding 12 two-hop rows.

Replace longer routes with shorter ones

As we build routes with more hops, it is logically possible that the `nextroutes` view will find shorter routes for an existing `routes` pair of `depart` and `arrive`. Standard SQL for replacing existing `routes` rows with `nextroutes` rows which match `(depart, arrive)` and have shorter `distance` values would be:

Listing 28

```
UPDATE routes SET (hops,route,distance,direction) = (
  SELECT hops, route, distance, direction
  FROM nextroutes
  WHERE nextroutes.depart = routes.depart AND nextroutes.arrive = routes.arrive
)
WHERE (depart,arrive) IN (
  SELECT depart,arrive FROM nextroutes
  WHERE nextroutes.distance < routes.distance
);
```

but MySQL does not support `SET(col1,...)` syntax, and as with *Listing 27*, MySQL does not yet accept subqueries referencing the table being updated, so we need more literal SQL:

Listing 29

```
UPDATE routes
JOIN nextroutes USING(arrive,depart)
```

```
SET
  routes.hops=nextroutes.hops,
  routes.route=nextroutes.route,
  routes.distance=nextroutes.distance,
  routes.direction=nextroutes.direction
WHERE nextroutes.distance < routes.distance;
```

Running this code right after the first run of Listing 27 updates no rows. To test the logic of iteration, continue running Listings 27 and 29 until no rows are being added or changed. The final result is:

```
SELECT * FROM ROUTES;
+----+--------+--------+------+-----------------+----------+-----------+
| id | depart | arrive | hops | route           | distance | direction |
+----+--------+--------+------+-----------------+----------+-----------+
|  1 | LAX    | JFK    |    1 | LAX,JFK         | 3941.18  | 8.61      |
|  2 | LHR    | JFK    |    1 | LHR,JFK         | 5550.77  | -171.68   |
|  3 | CDG    | JFK    |    1 | CDG,JFK         | 5837.46  | -173.93   |
|  4 | STL    | JFK    |    1 | STL,JFK         | 1408.11  | 7.44      |
|  5 | JFK    | LAX    |    1 | JFK,LAX         | 3941.18  | -171.39   |
|  6 | STL    | LAX    |    1 | STL,LAX         | 2553.37  | -170.72   |
|  7 | JFK    | LHR    |    1 | JFK,LHR         | 5550.77  | 8.32      |
|  8 | HEL    | LHR    |    1 | HEL,LHR         | 1841.91  | -161.17   |
|  9 | CDG    | LHR    |    1 | CDG,LHR         | 354.41   | 136.48    |
| 10 | ARN    | LHR    |    1 | ARN,LHR         | 1450.12  | -157.06   |
| 11 | LHR    | HEL    |    1 | LHR,HEL         | 1841.91  | 18.83     |
| 12 | CDG    | HEL    |    1 | CDG,HEL         | 1912.96  | 26.54     |
| 13 | ARN    | HEL    |    1 | ARN,HEL         | 398.99   | 6.92      |
| 14 | JFK    | CDG    |    1 | JFK,CDG         | 5837.46  | 6.07      |
| 15 | LHR    | CDG    |    1 | LHR,CDG         | 354.41   | -43.52    |
| 16 | HEL    | CDG    |    1 | HEL,CDG         | 1912.96  | -153.46   |
| 17 | ARN    | CDG    |    1 | ARN,CDG         | 1545.23  | -146.34   |
| 18 | JFK    | STL    |    1 | JFK,STL         | 1408.11  | -172.56   |
| 19 | LAX    | STL    |    1 | LAX,STL         | 2553.37  | 9.28      |
| 20 | LHR    | ARN    |    1 | LHR,ARN         | 1450.12  | 22.94     |
| 21 | HEL    | ARN    |    1 | HEL,ARN         | 398.99   | -173.08   |
| 22 | CDG    | ARN    |    1 | CDG,ARN         | 1545.23  | 33.66     |
| 23 | ARN    | JFK    |    2 | ARN,LHR,JFK     | 7000.89  | -157.06   |
```

```
| 24 | CDG    | LAX    |    2 | CDG,JFK,LAX     | 9778.64  | -173.93   |
| 25 | CDG    | STL    |    2 | CDG,JFK,STL     | 7245.57  | -173.93   |
| 26 | HEL    | JFK    |    2 | HEL,LHR,JFK     | 7392.68  | -161.17   |
| 27 | JFK    | ARN    |    2 | JFK,LHR,ARN     | 7000.89  | 8.32      |
| 28 | JFK    | HEL    |    2 | JFK,LHR,HEL     | 7392.68  | 8.32      |
| 29 | LAX    | CDG    |    2 | LAX,JFK,CDG     | 9778.64  | 8.61      |
| 30 | LAX    | LHR    |    2 | LAX,JFK,LHR     | 9491.95  | 8.61      |
| 31 | LHR    | LAX    |    2 | LHR,JFK,LAX     | 9491.95  | -171.68   |
| 32 | LHR    | STL    |    2 | LHR,JFK,STL     | 6958.88  | -171.68   |
| 33 | STL    | CDG    |    2 | STL,JFK,CDG     | 7245.57  | 7.44      |
| 34 | STL    | LHR    |    2 | STL,JFK,LHR     | 6958.88  | 7.44      |
| 35 | ARN    | LAX    |    3 | ARN,LHR,JFK,LAX | 10942.07 | -157.06   |
| 36 | ARN    | STL    |    3 | ARN,LHR,JFK,STL | 8409.00  | -157.06   |
| 37 | HEL    | LAX    |    3 | HEL,LHR,JFK,LAX | 11333.86 | -161.17   |
| 38 | HEL    | STL    |    3 | HEL,LHR,JFK,STL | 8800.79  | -161.17   |
| 39 | LAX    | ARN    |    3 | LAX,JFK,CDG,ARN | 10942.07 | 8.61      |
| 40 | LAX    | HEL    |    3 | LAX,JFK,CDG,HEL | 11333.86 | 8.61      |
| 41 | STL    | ARN    |    3 | STL,JFK,CDG,ARN | 8409.00  | 7.44      |
| 42 | STL    | HEL    |    3 | STL,JFK,CDG,HEL | 8800.79  | 7.44      |
+----+--------+--------+------+-----------------+----------+-----------+
```

All that's left to do is to assemble the code in a stored procedure:

Listing 30

```
DROP PROCEDURE IF EXISTS BuildRoutes;
DELIMITER go
CREATE PROCEDURE BuildRoutes()
BEGIN
  DECLARE rows INT DEFAULT 0;
  TRUNCATE routes;
  -- STEP 1, LISTING 24: SEED ROUTES WITH 1-HOP FLIGHTS
  INSERT INTO routes (depart, arrive, hops, route, distance, direction  )
    SELECT depart, arrive, 1, CONCAT(depart,',',arrive), distance, direction
  FROM flights;
  SET rows = ROW_COUNT();
  WHILE (rows > 0) DO
    -- STEP 2, LISTINGS 25, 27: ADD NEXT SET OF ROUTES
    INSERT INTO routes (depart, arrive, hops, route, distance, direction  )
```

```
      SELECT nextroutes.depart, nextroutes.arrive, nextroutes.hops,
        nextroutes.route, nextroutes.distance, nextroutes.direction
      FROM nextroutes
      LEFT JOIN routes ON nextroutes.depart=routes.depart AND nextroutes.arrive=routes.arrive
      WHERE routes.ID IS NULL;
      SET rows = ROW_COUNT();
    -- STEP 3, UPDATE SHORTER ROUTES IF ANY
    UPDATE routes
    JOIN nextroutes USING(arrive,depart)
    SET routes.hops=nextroutes.hops, routes.route=nextroutes.route,
        routes.distance=nextroutes.distance, routes.direction=nextroutes.direction
    WHERE nextroutes.distance < routes.distance;
  END WHILE;
END;
go
DELIMITER ;
```

The procedure looks like a candidate for translation a CTE, but update command and the two joins to `routes`, the table being written to, (one in the `nextroutes` View, one in the insert loop) defeat the CTE engines in both MariaDB and Postgres.

Route queries

Route queries are straightforward. How do we check that the algorithm produced no duplicate `depart-arrive` pairs? The following query should yield zero rows...

Listing 31

```
SELECT depart, arrive, COUNT(*)
FROM routes
GROUP BY depart,arrive
HAVING COUNT(*) > 1;
```

and does. *Reachability* queries are just as simple, for example where can we fly to from Helsinki?

Listing 32

```
SELECT *
FROM routes
```

```
WHERE depart='HEL'
ORDER BY distance;
+----+--------+--------+------+-----------------+----------+-----------+
| id | depart | arrive | hops | route           | distance | direction |
+----+--------+--------+------+-----------------+----------+-----------+
| 21 | HEL    | ARN    |    1 | HEL,ARN         | 398.99   | -173.08   |
|  8 | HEL    | LHR    |    1 | HEL,LHR         | 1841.91  | -161.17   |
| 16 | HEL    | CDG    |    1 | HEL,CDG         | 1912.96  | -153.46   |
| 26 | HEL    | JFK    |    2 | HEL,LHR,JFK     | 7392.68  | -161.17   |
| 38 | HEL    | STL    |    3 | HEL,LHR,JFK,STL | 8800.79  | -161.17   |
| 37 | HEL    | LAX    |    3 | HEL,LHR,JFK,LAX | 11333.86 | -161.17   |
+----+--------+--------+------+-----------------+----------+-----------+
```

An extended edge list model is simple to implement, gracefully accepts extended attributes for nodes, edge and paths, does not unduly penalise updates, and responds to queries with reasonable speed.

Parts explosions

A bill of materials for a house would include the cement block, lumber, shingles, doors, wallboard, windows, plumbing, electrical system, heating system, and so on. Each subassembly also has a bill of materials; the heating system has a furnace, ducts, and so on. A bill of materials implosion links component pieces to a major assembly. A bill of materials explosion breaks apart assemblies and subassemblies into their component parts.

Which graph model best handles a parts explosion? Combining edge list and nested sets algorithms seems a natural solution.

Imagine a company that plans to make variously sized bookcases, either packaged as do-it-yourself kits of, or assembled from sides, shelves, shelf brackets, backboards, feet and screws. Shelves and sides are cut from planks. Backboards are trimmed from laminated sheeting. Feet are machine-carved from readycut blocks. Screws and shelf brackets are purchased in bulk. Here are the elements of one bookcase:

```
  1 backboard, 2 x 1 m
    1 laminate
```

```
    8 screws
  2 sides 2m x 30 cm
    1 plank length 4m
    12 screws
  8 shelves 1 m x 30 cm (incl. top and bottom)
    2 planks
    24 shelf brackets
  4 feet 4cm x 4cm
    4 cubes
    16 screws
```

which may be packaged in a box for sale at one price, or assembled as a finished product at a different price. At any time we need to be able to answer questions like

- Do we have enough parts to make the bookcases on order?
- What assemblies or packages would be most profitable to make given the current inventory?

To normalise, put items and their details in a nodes table and assembly information in an edges table. Note that often, as in our example ...

- an item occurs in multiple subassemblies (e.g., many parts require screws), so the graph is *cyclic*, not a tree.
- it would be cumbersome to require creation of a new assembly table for each new product, so the assemblies table should track multiple products.

Then let one row in the *items* (nodes) table define a component with columns for ID, name, quantity on hand, quantity reserved, purchase cost and labour/assembly cost. An item may be simple (e.g., a plank), complex (e.g., a backboard consisting of a laminate and 8 screws), or a complete product (e.g., an assembled bookcase). The items table tracks inventory.

Let one row in the *assemblies* (edges) table define a parent-child relationship between two items in a subassembly. Then a subassembly is a set of such rows, and a product is set of such subassemblies.

Assume that the company begins with a plan to sell the 2m x 1m bookcase in two forms, assembled and kit, and that the purchasing department has bought quantities of raw materials (laminate, planks, shelf supports, screws, wood cubes, boxes). Here are the nodes (items) and edges (assemblies):

Listing 33

```
CREATE TABLE items (
  itemID INT PRIMARY KEY AUTO_INCREMENT,
  name CHAR(20) NOT NULL,
  onhand INT NOT NULL DEFAULT 0,
  reserved INT NOT NULL DEFAULT 0,
  purchasecost DECIMAL(10,2) NOT NULL DEFAULT 0,
  assemblycost DECIMAL(10,2) NOT NULL DEFAULT 0,
  price DECIMAL(10,2) NOT NULL DEFAULT 0
);
CREATE TABLE assemblies (
  assemblyID INT NOT NULL,
  assemblyroot INT NOT NULL,
  childID INT NOT NULL,
  parentID INT NOT NULL,
  quantity DECIMAL(10,2) NOT NULL,
  assemblycost DECIMAL(10,2) NOT NULL,
  PRIMARY KEY(assemblyID,childID,parentID)
);
INSERT INTO items VALUES    -- inventory
  (1,'laminate',40,0,4,0,8),(2,'screw',1000,0,0.1,0,.2),(3,'plank',200,0,10,0,20),
  (4,'shelf bracket',400,0,0.20,0,.4),(5,'wood cube',100,0,0.5,0,1),(6,'box',40,0,1,0,2),
  (7,'backboard',0,0,0,3,0),(8,'side',0,0,0,8,0),(9,'shelf',0,0,0,4,0),
  (10,'foot',0,0,0,1,0),(11,'bookcase2x30',0,0,0,10,0),(12,'bookcase2x30 kit',0,0,0,2,0);
INSERT INTO assemblies VALUES
  (1,11,1,7,1,0),      -- laminate to backboard
  (2,11,2,7,8,0),      -- screws to backboard
  (3,11,3,8,.5,0),     -- planks to side
  (4,11,2,8,6,0),      -- screws to side
  (5,11,3,9,0.25,0),   -- planks to shelf
  (6,11,4,9,4,0),      -- shelf brackets to shelf
  (7,11,5,10,1,0),     -- wood cubes to foot
  (8,11,2,10,1,0),     -- screws to foot
  (9,11,7,11,1,0),     -- backboard to bookcase
  (10,11,8,11,2,0),    -- sides to bookcase
  (11,11,9,11,8,0),    -- shelves to bookcase
  (12,11,10,11,4,0),   -- feet to bookcase
  (13,12,1,7,1,0),     -- laminate to backboard
```

```
  (14,12,2,7,8,0),     -- screws to backboard
  (15,12,3,8,0.5,0),   -- planks to side
  (16,12,2,8,6,0),     -- screws to sides
  (17,12,3,9,0.25,0),  -- planks to shelf
  (18,12,4,9,4,0),     -- shelf brackets to shelves
  (19,12,5,10,1,0),    -- wood cubes to foot
  (20,12,2,10,1,0),    -- screws to foot
  (21,12,7,12,1,0),    -- backboard to bookcase kit
  (22,12,8,12,2,0),    -- sides to bookcase kit
  (23,12,9,12,8,0),    -- shelves to bookcase kit
  (24,12,10,12,4,0),   -- feet to bookcase kit
  (25,12,6,12,1,0);    -- container box to bookcase kit
```

Now, we want a parts list, a bill of materials showing parent-child relationships, quantities, and costs. Could we adapt the depth-first nested sets treewalk algorithm (*Listing 10*) to this problem even when our graph is not a tree and our sets are not properly nested? Yes: touch up the treewalk to handle multiple parent nodes for any child node, and add code to percolate quantities and costs up the graph. Navigation remains simple using `leftedge` and `rightedge` values.

Listing 34

```
DROP PROCEDURE IF EXISTS ShowBOM;
DELIMITER go
CREATE PROCEDURE ShowBOM( IN root INT )
BEGIN
  DECLARE thischild, thisparent, rows, maxrightedge INT DEFAULT 0;
  DECLARE thislevel, nextedgenum INT DEFAULT 1;
  DECLARE thisqty, thiscost DECIMAL(10,2);
  -- Create and seed intermediate table:
  DROP TABLE IF EXISTS edges;
  CREATE TABLE edges (
    childID smallint NOT NULL,
    parentID smallint NOT NULL,
    PRIMARY KEY (childID, parentID)
  ) ENGINE=HEAP;
  INSERT INTO edges
    SELECT childID,parentID
    FROM assemblies
    WHERE assemblyRoot = root;
```

```
SET maxrightedge = 2 * (1 + (SELECT COUNT(*) FROM edges));
-- Create and seed result table:
DROP TABLE IF EXISTS bom;
CREATE TABLE bom (
  level SMALLINT,
  nodeID SMALLINT,
  parentID SMALLINT,
  qty DECIMAL(10,2),
  cost DECIMAL(10,2),
  leftedge SMALLINT,
  rightedge SMALLINT
) ENGINE=HEAP;
INSERT INTO bom VALUES( thislevel, root, 0, 0, 0, nextedgenum, maxrightedge );
SET nextedgenum = nextedgenum + 1;
WHILE nextedgenum < maxrightedge DO
  -- How many children of this node remain in the edges table?
  SET rows = (
    SELECT COUNT(*)
    FROM bom AS p
    JOIN edges AS c ON p.nodeID=c.parentID AND p.level=thislevel
  );
  IF rows > 0 THEN
    -- Child edge exists. Compute qty & cost, insert in bom, delete from edges.
    BEGIN
      -- Alas MySQL nulls MIN(t.childid) when we combine the next two queries
      SET thischild = (
        SELECT MIN(c.childID)
        FROM bom AS p
        INNER JOIN edges AS c ON p.nodeID=c.parentID AND p.level=thislevel
      );
      SET thisparent = (
        SELECT DISTINCT c.parentID
        FROM bom AS p
        INNER JOIN edges AS c ON p.nodeID=c.parentID AND p.level=thislevel
      );
      SET thisqty = (
        SELECT quantity FROM assemblies
        WHERE assemblyroot = root
```

```
          AND childID = thischild
          AND parentID = thisparent
      );
      SET thiscost = (
        SELECT thisqty * ( a.assemblycost + i.purchasecost + i.assemblycost )
        FROM assemblies AS a
        JOIN items AS i ON a.childID = i.itemID
        WHERE assemblyroot = root
          AND a.parentID = thisparent
          AND a.childID = thischild
      );
      INSERT INTO bom
        VALUES(thislevel+1, thischild, thisparent, thisqty, thiscost, nextedgenum, NULL);
      DELETE FROM edges WHERE childID=thischild AND parentID=thisparent;
      SET thislevel = thislevel + 1, nextedgenum = nextedgenum + 1;
    END;
  ELSE
    BEGIN
      -- Set rightedge, remove item from edges
      UPDATE bom
      SET rightedge=nextedgenum, level = -level
      WHERE level = thislevel;
      SET thislevel = thislevel – 1, nextedgenum = nextedgenum + 1;
    END;
  END IF;
END WHILE;
SET rows := ( SELECT COUNT(*) FROM edges );
IF rows > 0 THEN
  SELECT 'Orphaned rows remain';
ELSE
  BEGIN
    SET thiscost = (SELECT SUM(cost*qty) FROM bom);
    UPDATE bom SET qty=1, cost=thiscost WHERE nodeID = root;
    SELECT
      CONCAT(Space(Abs(level)*2), ItemName(nodeid,root)) AS Item,
      ROUND(qty,1) AS Qty,
      ROUND(cost,2) AS Cost
    FROM bom
```

```
      ORDER BY leftedge;
    END;
  END IF;
END;
go
DELIMITER ;
CALL SHOWBOM(11);
+---------------------+------+--------+
| Item                | Qty  | Cost   |
+---------------------+------+--------+
|   BOOKCASE2X30      |  1.0 | 327.93 |
|     backboard       |  1.0 |   3.00 |
|       laminate      |  1.0 |   4.00 |
|       screw         |  8.0 |   0.80 |
|     side            |  2.0 |  16.00 |
|       screw         |  6.0 |   0.60 |
|       plank         |  0.5 |   5.00 |
|     shelf           |  8.0 |  32.00 |
|       plank         |  0.3 |   2.50 |
|       shelf bracket |  4.0 |   0.80 |
|     foot            |  4.0 |   4.00 |
|       screw         |  1.0 |   0.10 |
|       wood cube     |  1.0 |   0.50 |
+---------------------+------+--------+
```

With ShowBOM( ) in hand, it's easy to compare costs of assemblies and subassemblies. By adding price columns, we can do the same for prices and profit margins. And now that MySQL has re-enabled prepared statements in stored procedures, it will be relatively easy to write a more general version of ShowBOM( ).

Shorter and sweeter

But ShowBOM() is not the small, efficient bit of nested sets reporting code we'd hoped for from the nested sets model. There is a simpler solution: hide the graph cycles from the edges table by making them references to rows in a nodes table, so we can treat the edges table like a tree; then apply a breadth-first *edge-list subtree algorithm* to generate the Bill of Materials. Again assume a cabinetmaking company making bookcases. The costing model differs a bit from Listing 33, and for clarity

we skip inventory tracking. An items table `ww_nodes` tracks purchased and assembled bookcase elements with their individual costs, and an assemblies/edges `ww_edges` table tracks sets of edges that combine to make products.

Listing 35: DDL for a simpler parts explosion

```
DROP TABLE IF EXISTS ww_nodes;
CREATE TABLE ww_nodes (
  nodeID int,
  description CHAR(50),
  cost decimal(10,2)
);
INSERT INTO ww_nodes VALUES
(1,'finished bookcase',10),(2,'backboard2x1',1),(3,'laminate2x1',8),(4,'screw',.10),
(5,'side',4),(6,'plank',20),(7,'shelf',4),(8,'shelf bracket',.5),(9,'foot',1),
(10,'cube4cmx4cm',1),(11,'bookcase kit',2),(12,'carton',1);
DROP TABLE IF EXISTS ww_edges;
CREATE TABLE ww_edges (
  rootID INT,
  nodeID int,
  parentnodeID int,
  qty decimal(10,2)
);
INSERT INTO ww_edges VALUES (1,1,null,1), -- root
(1,2,1,1),(1,3,2,1),(1,4,2,8),(1,5,1,2),(1,6,5,1),(1,4,5,12),
(1,7,1,8),(1,6,7,.5),(1,8,7,4),(1,9,1,4),(1,10,9,1),(1,4,9,1),
(11,11,null,1),                              -- root for kit
(11,2,11,1),(11,3,2,1),(11,4,2,8),(11,5,11,2),(11,6,5,1),(11,4,5,12),(11,7,11,8),
(11,6,7,.5),(11,8,7,4),(11,9,11,4),(11,10,9,1),(11,4,9,11),(11,12,11,1);
```

Here is an adapted breadth-first edge list Bill of Materials for a product identified by a `rootID`:

- Initialise a level-tracking variable to zero.
- Seed a `temp` reporting table with the `rootID` of the desired product.
- While rows are being retrieved, increment the level tracking variable and add rows to the `temp` table whose `parentnodeIDs` are nodes at the current level.
- Percolate costs up the graph from child to parent

- Print the BOM ordered by path to each item, indented proportionally to graph level.

Listing 36: Simpler parts explosion

```
DROP PROCEDURE IF EXISTS ww_bom;
DELIMITER go
CREATE PROCEDURE ww_bom( root INT )
BEGIN
  DECLARE lev INT DEFAULT 0;
  DECLARE totalcost DECIMAL( 10,2);
  DROP TABLE IF EXISTS temp;
  CREATE TABLE temp                                  -- initialise temp table with root node
  SELECT
    e.nodeID AS nodeID,
    n.description AS Item,
    e.parentnodeID,
    e.qty,
    n.cost AS nodecost,
    e.qty * n.cost AS cost,
    0 as level,                                      -- tree level
    CONCAT(e.nodeID,'') AS path                      -- path to this node as a string
  FROM ww_nodes n
  JOIN ww_edges e USING(nodeID)                      -- root node
  WHERE e.nodeID = root AND e.parentnodeID IS NULL;
  WHILE FOUND_ROWS() > 0 DO
    BEGIN
      SET lev = lev+1;                               -- increment level
      INSERT INTO temp                               -- add children of this level
      SELECT
        e.nodeID,
        n.description AS Item,
        e.parentnodeID,
        e.qty,
        n.cost AS nodecost,
        e.qty * n.cost AS cost,
        lev,
        CONCAT(t.path,',',e.nodeID)
      FROM ww_nodes n
```

```
      JOIN ww_edges e USING(nodeID)
      JOIN temp t ON e.parentnodeID = t.nodeID
      WHERE e.rootID = root AND t.level = lev-1;
    END;
  END WHILE;
  WHILE lev > 0 DO                                  -- percolate costs up the graph
    BEGIN
      SET lev = lev - 1;
      DROP TABLE IF EXISTS tempcost;
      CREATE TABLE tempcost                         -- compute child cost
      SELECT p.nodeID, SUM(c.nodecost*c.qty) AS childcost
      FROM temp p
      JOIN temp c ON p.nodeid=c.parentnodeid
      WHERE c.level=lev
      GROUP by p.nodeid;
      UPDATE temp JOIN tempcost USING(nodeID)       -- update parent item cost
      SET nodecost = nodecost + tempcost.childcost;
      UPDATE temp SET cost = qty * nodecost         -- update parent cost
      WHERE level=lev-1;
    END;
  END WHILE;
  SELECT                                            -- list BoM
    CONCAT(SPACE(level*2),Item) AS Item,
    ROUND(nodecost,2) AS 'Unit Cost',
    ROUND(Qty,0) AS Qty,ROUND(cost,2) AS Cost FROM temp
  ORDER by path;
END;
go
DELIMITER ;
CALL ww_bom( 1 );
+-------------------+-----------+------+--------+
| Item              | Unit Cost | Qty  | Cost   |
+-------------------+-----------+------+--------+
| finished bookcase |    206.60 |  1.0 | 206.60 |
|   backboard2x1    |      9.80 |  1.0 |   9.80 |
|     laminate2x1   |      8.00 |  1.0 |   8.00 |
|     screw         |      0.10 |  8.0 |   0.80 |
|   side            |     25.20 |  2.0 |  50.40 |
```

```
|     screw          |      0.10 | 12.0 |   1.20 |
|     plank          |     20.00 |  1.0 |  20.00 |
|   shelf            |     16.00 |  8.0 | 128.00 |
|     plank          |     20.00 |  0.5 |  10.00 |
|     shelf bracket  |      0.50 |  4.0 |   2.00 |
|   foot             |      2.10 |  4.0 |   8.40 |
|     cube4cmx4cm    |      1.00 |  1.0 |   1.00 |
|     screw          |      0.10 |  1.0 |   0.10 |
+--------------------+-----------+------+--------+
```

Summary

Stored routines and Views make it possible to implement edge list graph models, nested sets graph models, and breadth-first and depth-first graph search algorithms since MySQL 5. Common Table Expressions in MariaDB since version 10.2.2 and MySQL since version 8.0.1 greatly improve edge list query performance.

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