Generating Test Data for Killing SQL Mutants : A Constraint based Approach

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Outline

- Motivation
- Mutation Testing
- Related Work
- Contributions
- Implementation[XDa-TA]
- Experiments
- Extensions
- Future Work

Testing SQL Queries : A Challenge

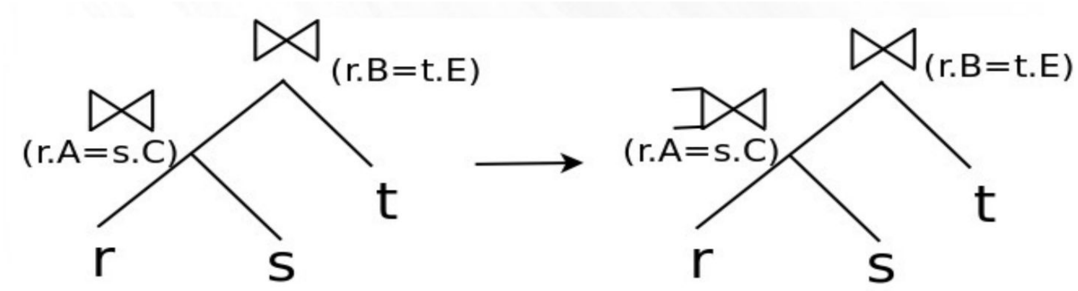
- Complex SQL queries hard to get right
- **Question**: How to check if an SQL query is correct?
    - Formal verification is not applicable since we do not have a separate specification and an implementation
    - State of the art solution: manually generate test databases and check if the query gives the intended result
        - Often misses errors

Generating Test Data: Prior Work

- Automated Test Data generation
    - Based on database constraints, and SQL query
        - Agenda [Chays et al., STVR04]
    - Reverse Query Processing [Binning et al., ICDE07]
        - takes desired query output and generates relation instances
        - Handle a subset of Select/Project/Join/GroupBy queries
    - Extensions of RQP for performance testing
        - guarantees cardinality requirements on relations and intermediate query results
- None of the above guarantee anything about detecting errors in SQL queries
- **Question**: How do you model SQL errors? **Answer**: Query Mutation

Mutation Testing

- Mutant: Variation of the given query
- Mutations model common programming errors, like
  - Join used instead of outerjoin (or vice versa)
  - Join/selection condition errors
    - < vs. <=, missing or extra condition
  - Wrong aggregate (min vs. max)
- Mutant may be the intended query



Mutation Testing of SQL Queries

- Traditional use of mutation testing has been to check coverage of dataset
  - Generate mutants of the original program by modifying the program in a controlled manner
  - A dataset **kills** a mutant if query and the mutant give different results on the dataset
  - A dataset is considered **complete** if it can kill all non-equivalent mutants of the given query
- **Our goal**: generating dataset for testing query
  - Test dataset and query result on the dataset are shown to human, who verifies that the query result is what is expected given this dataset
  - Note that we do not need to actually generate and execute mutants

Related Work

- Tuya and Suarez-Cabal [IST07], Chan et al. [QSIC05] defined a class of SQL query mutations
  - Shortcoming: do not address test data generation
- More recently (and independent of our work) de la Riva et al [AST10] address data generation using constraints, with the **Alloy** solver
  - Do not consider alternative join orders
  - No completeness results
  - Limitations on constraints

Contributions

- Principled approach to test data generation for given query
- Define class of mutations:
  - Join/outerjoin
  - Selection condition
  - Aggregate function
- Algorithm for test data generation that kills all non-equivalent mutants in above class for a (fairly large) subset of SQL.
  - Under some simplifying assumptions
  - With the guarantee that generated datasets are small and realistic, to aid in human verification of results

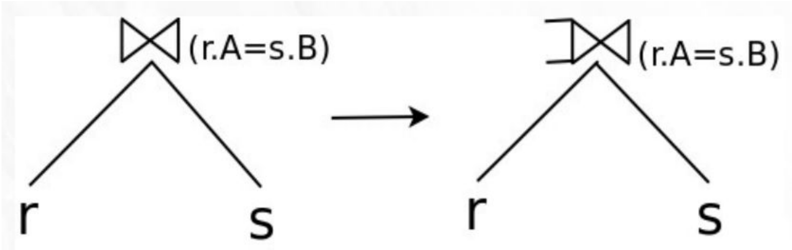
NP Hardness of Data Generation Problem

- Data Generation Problem : *Is there an assignment of tuples to each relation in query , Q such that the result of Q and its mutation Q' differ?*
- Query Containment Problem: Given two SQL queries Q_1 and Q_2, is Q_2 contained in Q_1 ? (Already known to be NP-complete)
- Reduction: Consider $Q_2 \bowtie Q_1$ and Q_2 ⟕ Q_1.
  - If Data Generation Problem assigns tuples to the relation in Q_1 and Q_2 such that the results of above two trees differ than Q_2 is not contained in Q_1.
  - If there is no such assignment, Q_2 is contained in Q_1.

Killing Join Mutants : Example 1

Example 1: Without foreign key constraints

Schema: r(A), s(B)

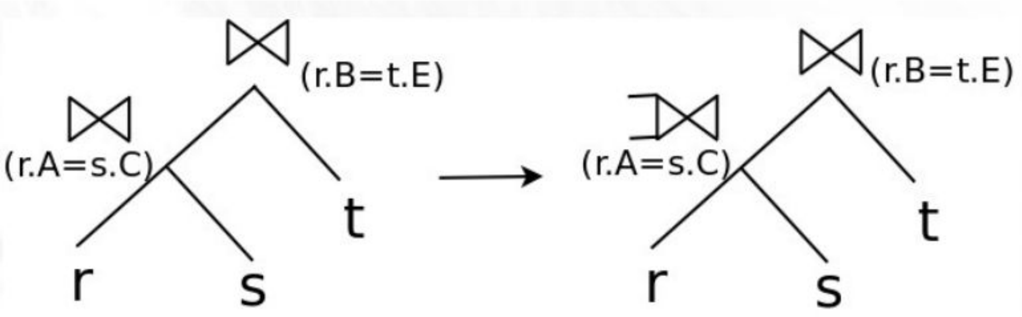


- To kill this mutant: ensure that for some ***r*** tuple there is no matching ***s*** tuple
- Generated test case: r(A)={(1)}; s(B)={}
- Basic idea, version 1 [ICDE 2010]
  - run query on given database
  - from result extract matching tuples for r and s
  - delete s tuple to ensure no matching tuple for r
- Limitation: foreign keys, repeated relations

Killing Join Mutants : Example 2

Example 2: Extra join above mutated node

Schema: r(A,B), s(C,D), t(E)

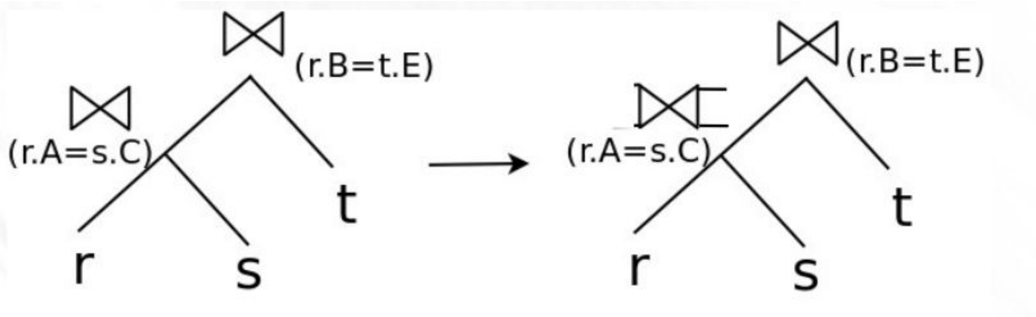


- To kill this mutant we must ensure that for an ***r*** tuple there is no matching ***s*** tuple, but there is a matching ***t*** tuple
- Generated test case: r(A,B)={(1,2)}; s(C,D)={}; t(E)={(2)}

Killing Join Mutants : Example 3

Example 3: Equivalent mutation due to join

Schema: r(A,B), s(C,D), t(E)



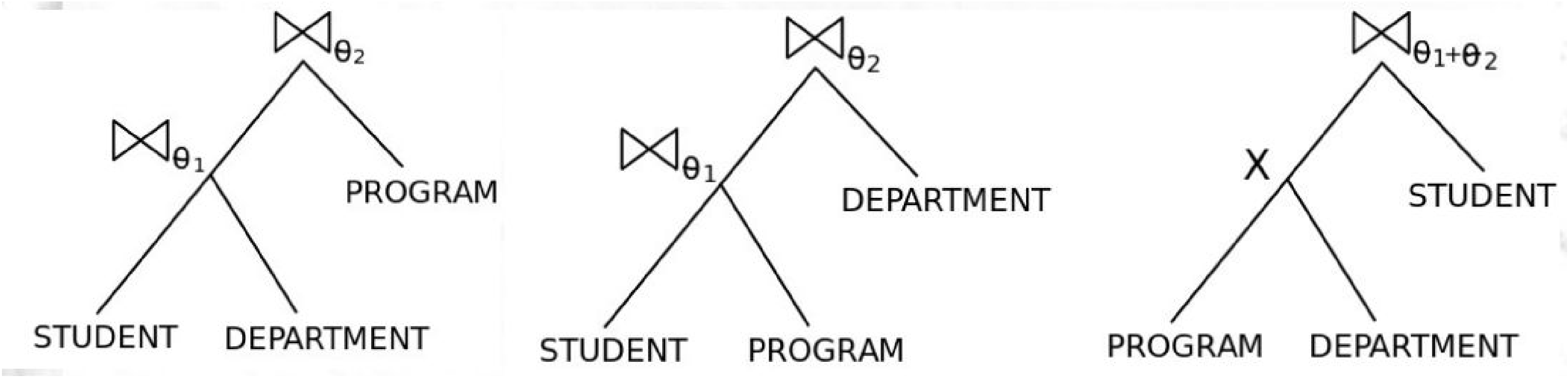
- Note: right outer join this time
- Any result with a ***r.B*** being *null* will be removed by join with ***t***
- Similarly equivalence can result due to selections

Killing Join Mutants : Example 4

- ***teaches*** ⟕ ***instructor*** is equivalent to ***teaches*** $\bowtie$ ***instructor*** if there is a foreign key from ***teaches.ID*** to ***instructor.ID***
- The two expressions are no longer equivalent if ***instructor*** is replaced with
  $$\sigma_{instructor.dept=\mathrm{CS}}(instructor)$$

- Key idea: have a ***teaches*** tuple with an ***instructor*** not from CS
- Selections and joins can be used to kill mutations

Killing Join Mutants: Equivalent Trees

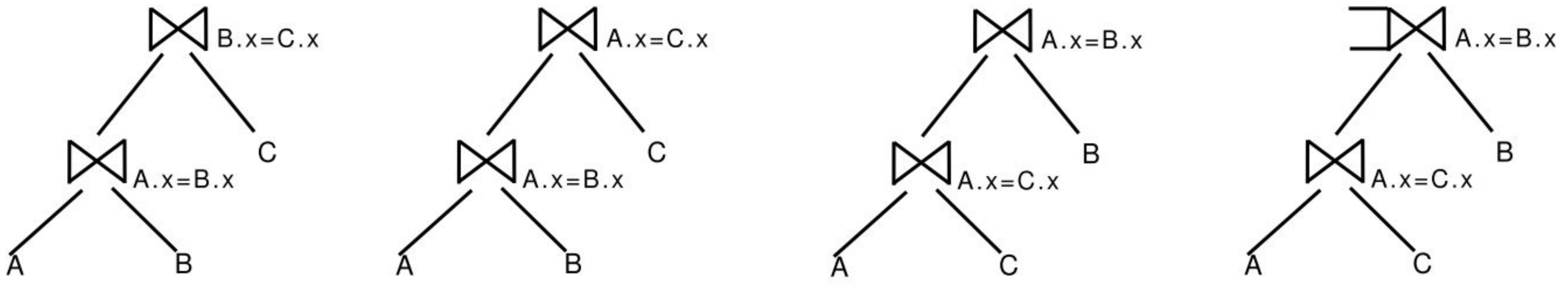


- **Space of join-type mutants**: includes mutations of join operator of a single node for all trees equivalent to given query tree
- Datasets should kill mutants across all such trees

Killing Join Mutants: Equivalent Trees

Whether a query is written in the form **A.x = B.x AND B.x = C.x**, or **A.x = B.x AND A.x = C.x** should not affect set of mutants generated

Solution: Equivalence classes of attributes

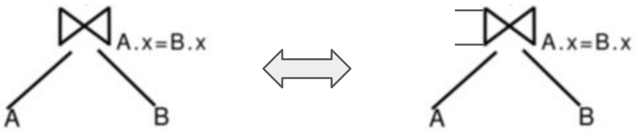


a. Given Query b. Equivalent Query c. Join Reordering on (b) d. Intended Query

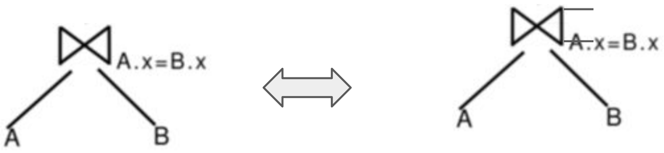
Assumptions

- A1, A2: Only primary and foreign key constraints; foreign key columns not nullable
- A3: Single block SQL queries; no nested subqueries
- A4: Expr/functions: Only arithmetic expressions
- A5: Join/selection predicates : conjunctions of *{expr relop expr}*
- A6: Queries do not explicitly check for null values using IS NULL
- A7: In the presence of full outer join, at least one attribute from each of its inputs present in the select clause (and A8 for natural join: see paper)

Generating Constraints to kill Join Mutations



There exists a tuple in *A* for which there does not exist any matching tuple in *B*.



There exists a tuple in *B* for which there does not exist any matching tuple in *A*.

Problems

- Translate high level requirements into constraints on individual tuples
- Ensure the difference exposed at an internal node is propagated to root
- Exponential number of join trees
- Repeated relation occurences

Data Generation in 2 Steps

- Step 1: Generation of constraints
  - Constraints due to the schema
  - Constraints due to the query
  - Constraints to kill a specific mutant
- Step 2: Generation of data from constraints Using solver, currently CVC3

Data Generation Algorithm : Overview

Algorithm 1 : Main Algorithm

```
Hashtable currentIndex; /* Maps distinct relation names to offsets in the CVC3 array created for the corresponding database relation */
procedure generateDataSet(query q)
    preprocess query tree
    initializeIndices() /* Initializes currentIndex
        and other related structures */
    generateDataSetForOriginalQuery()
    killEquivalenceClasses()
    killOtherPredicates()
    killComparisonOperators()
    killAggregates()
end procedure
```

Preprocess Query Tree

- Build Equivalence Classes from join conditions
  - A.x = B.y and B.y = C.z
  - Equivalence class: A.x, B.y and C.z
- Foreign Key Closure –
  - A.x -> B.y and B.y -> C.z then A.x -> C.z
- Retain all join/selection predicates other than equijoin predicates

Helper Functions

- CvcMap(*rel.attr*)
  - Takes a *rel* and *attr* and returns r[i].pos where
    - *r* is base relation of *rel*
    - *pos* is the position of attribute *attr*
    - *i* is an index in the tuple array *
- GenerateEqConds(P)
  - Generates equality constraints amongst all elements of an equivalence class P

Killing Equi Join Condition Mutations

Algorithm 2 : killEquivalenceClasses()

for each equivalence class ec **do**
    Let $allRelations$:= Set of all $\langle rel, attr\rangle$ pairs in ec
    for each element e in $allRelations$ **do**
        $conds$:= empty set
        Let e := $R.a$
        S := (set of elements in ec which are foreign keys referencing $R.a$ directly or indirectly) UNION $R.a$
        P := ec - S
        if P.isEmpty() **then**
            continue
        end if
        $conds$.add(generateEqConds(P))
        $conds$.add(
            "NOT EXISTS i: R[i].a = " + cvcMap(P[0]))

Killing Equi Join Condition Mutations (contd.)

```
        for all other equivalence classes oec do
            conds.add(generateEqConds(oe))
        end for
        for each other predicate p do
            conds.add(cvcMap(p))
        end for
        conds.add(genDBConstraints())
        callSolver(conds)
        if solution exists then
            create a dataset from solver output
        end if
    end for
end for
```

Killing Other Predicates

- Create separate dataset for each attribute in predicate
- e.g. For Join condition B.x = C.x + 10
    - Dataset 1 (nullifying B:x):
      ASSERT NOT EXISTS (i : B_INT) : (B[i].x = C[1].x + 10);
    - Dataset 2 (nullifying C:x):
      ASSERT NOT EXISTS (i : C_INT) : (B[1].x = C[i].x + 10);

Killing Comparison Operator Mutations

- Example of comparison operation mutations:
    - A < 5 vs. A <= 5 vs. A > 5 vs A >= 5 vs. A=5, vs A <> 5
- Idea: generate separate dataset for three cases (leaving rest of query unchanged):
    - A < 5
    - A = 5
    - A > 5
- This set will kill all above mutations

Killing Unconstrained Aggregation Mutations

- Aggregation operations
  - count(A) vs. count(distinct A)
  - sum(A) vs sum(distinct A)
  - avg(A) vs avg(distinct A)
  - min(A) vs max(A)
  - and mutations amongst all above operations
- Idea: given relation *r(G, O, A)* and query select aggop*(A)* from r group by G Tuples (g1, o1, a1), (g1, o2, a1), (g1, o3, a2) , with a1 <> 0 will kill above pairs of mutations
- Additional constraints to ensure killing mutations across pairs

Aggregation Operation Mutation

- Issues:
    - Database/query constraints forcing A to be unique for a given G
    - Database/query constraints forcing A to be a key
    - Database/query constraints forcing G to be a key
- Carefully crafted set of constraints, which are relaxed to handle such cases

Completeness Results

Theorem: For the class of queries, with the space of join-type and selection mutations defined in the paper, the suite of datasets generated by our algorithm is complete. That is, the datasets kill all non-equivalent mutations of a given query

- Completeness results for restricted classes of aggregation mutations
  - aggregation as top operation of tree, under some restrictions on joins in input

Experimental Results

- x86 machines, 1.86 GHz processor, 2 GB main memory
- Schema: University database from Database System COncepts (6^{th} ed.)
- Queries with joins with varying number of foreign keys imposed
- Queries with comparison, aggregation and inner joins

Inner Join Queries

Query	#Joins (#Relations)	#FK	#Datasets Generated	#Mutants Killed	Total Time(s) without Unfolding	Total Time(s) with Unfolding
1	1 (2)	0	2	2	0.430	0.040
1	1 (2)	1	1	1	0.370	0.030
2	2 (3)	0	4	6	1.680	0.140
2	2 (3)	1	3	4	1.000	0.100
2	2 (3)	2	2	3	0.990	0.060
3	3 (4)	0	6	18	3.990	0.229
3	3 (4)	1	5	13	1.729	0.190
3	3 (4)	4	3	6	1.230	0.179
4	4 (5)	0	7	122	7.190	0.279
4	4 (5)	4	4	62	2.310	0.190
5	5 (6)	0	9	450	26.800	0.570
5	5 (6)	4	6	245	2.960	0.380
6	6 (7)	0	11	1499	68.450	0.790
6	6 (7)	6	6	507	3.809	0.520

TABLE I
RESULTS FOR INNER JOIN QUERIES

Selection/Aggregation Queries

Query	#Joins	#Selections	#Aggregations	#Data sets Gen.	#Mutants killed	Total Time(s) without Unfolding	Total Time(s) with Unfolding
7	0	1	0	3	5	0.12	0.12
8	0	0	1	1	7	0.08	0.08
9	1	0	1	2	9	41.40	0.65
10	2	1	0	6	9	5.69	1.23
11	2	2	0	9	18	6.54	1.67
12	2	1	1	5	14	53.95	1.05

TABLE II
RESULTS FOR QUERIES WITH SELECTION/AGGREGATION

Extensions

- Handling Nulls
- String Constraints
- Constrained Aggregation

Source :
Extending XData to kill SQL query mutants in the wild

Handling Nulls

- For text attributes, enumerate a few more values in the enumerated type and designate them NULLs.
  - Example : for an attribute course_id, we enumerate values NULL_course_id_1, NULL_course_id_2, etc.
- For numeric values, we model NULLs as any integer in a range of negative values that we define to be not part of the allowable domain of that numeric value.
- Add constraints forcing those attribute values to take on one of the above mentioned special values representing NULL.
- Add constraints to force all other values to be non null
- Enables handling of nullable foreign keys, and explicit IS NULL checks

String Constraints

- String Constraints
  - S1 likeop pattern
  - S1 relop constant
  - strlen(S) relop constant
  - S1 relop S2

where

- S1 and S2 are string variables,
- *likeop* is one of LIKE, ILIKE (case insensitive like),NOT LIKE and NOT ILIKE
- *relop* operators are =, <, ≤, >, ≥, <>, and case-insensitive equality denoted by =.

String Constraints

- String solver
- String constraint mutation: {=, <>, <, >, ≤, ≥}
    - S1 = S2
    - S1 > S2
    - S1 < S2
- LIKE predicate mutation: {LIKE, ILIKE,NOT LIKE, NOT ILIKE }
    - Dataset 1 satisfying the condition S1 LIKE pattern.
    - Dataset 2 satisfying condition S1 ILIKE pattern, but not S1 LIKE pattern
    - Dataset 3 failing both the LIKE and ILIKE conditions

Constrained Aggregation Operation

- Aggregation Constraints: Example : SUM (r.a) > 20
- CVC3 requires us to specify how many tuples r has.
- Hence, before generating CVC3 constraints we must

  (a) estimate the number of tuples n, required to satisfy an aggregation constraint

  (b) translate this number n to appropriate number of tuples for each base relation so that the input of the aggregation contains exactly n tuples.

XDa-TA System

- For each query in an assignment, a correct SQL query is given to the tool, which generates datasets for killing mutants of that query.
- Modes:
  - admin mode
  - student mode.
- Assignment can be marked as :
  - learning assignment
  - graded assignment.

Source:
XDa-TA : Automating Grading of SQL Query Assignments

Sample Query Set

QId	DS	Query
Q5	8	SELECT DISTINCT course.dept_name FROM course NATURAL JOIN section WHERE section.semester='Spring' AND section.year='2010'
Q7	4	SELECT course_id, COUNT(DISTINCT id) FROM course NATURAL LEFT OUTER JOIN takes GROUP BY course_id
Q8	11	SELECT DISTINCT course_id, title FROM course NATURAL JOIN section WHERE semester = 'Spring' and year = 2010 and course_id not in (SELECT course_id FROM prereq)
Q10	6	SELECT DISTINCT dept_name FROM course WHERE credits = (SELECT max(credits) FROM course)
Q12	4	SELECT student.id, student.name FROM student WHERE lower(student.name) like '%sr%'
Q14	6	SELECT DISTINCT * FROM takes T WHERE (NOT EXISTS (SELECT id, course_id FROM takes S WHERE grade $\neq$ 'F' AND T.id = S.id AND T.course_id = S.course_id) and T.grade IS NOT NULL) or (grade $\neq$ 'F' AND T.grade IS NOT NULL)

Results

QId	Queries	XData		Univ. sm.		Univ. lg.		TA	
		√	×	√	×	√	×	√	×
Q1	55	53	2	53	2	53	2	53	2
Q2	57	56	1	56	1	56	1	56	1
Q3	71	58	13	59	12	59	12	70	1
Q4	78	52	26	52	26	75	3	77	1
Q5	72	49	23	61	11	56	16	59	13
Q6	61	55	6	55	6	55	6	59	2
Q7	77	52	25	54	23	75	3	53	24
Q8	79	46	33	67	12	65	14	63	16
Q9	80	37	43	56	24	10	70	57	23
Q10	74	73	1	73	1	73	1	74	0
Q11	69	53	16	53	16	53	16	53	16
Q12	70	62	8	67	3	63	7	63	7
Q13	72	64	8	63	9	63	9	65	7
Q14	67	58	9	53	14	57	10	32	35
Q15	72	72	0	72	0	72	0	72	0

Future Work

- Integration with course management systems such as Moodle or Blackboard using the Learning Tools Interoperability (LTI) standard (complete)
- Partial Marking Scheme implementation (ongoing)
- Future work:
  - Handling SQL features not supported currently
  - Multiple queries
  - Form parameters

Thank You!

Questions?