Detecting Logic Bugs in Graph Database Management Systems via Injective and Surjective Graph Query Transformations

Yuancheng Jiang, Jiahao Liu, Jinsheng Ba
Roland Yap, Zhenkai Liang, Manuel Rigger

NUS
National University of Singapore

Database Systems: Relational vs. Graph

MySQL, SQLite, PostgreSQL, ORACLE, MariaDB Foundation, CockroachDB

Relational Data Model

Students

ID	Name
001	Sam
002	Mary
003	Tine
004	Jay

StudentCourses

StudentId	CourseId
001	1
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...	...

Courses

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2	ASP.NET
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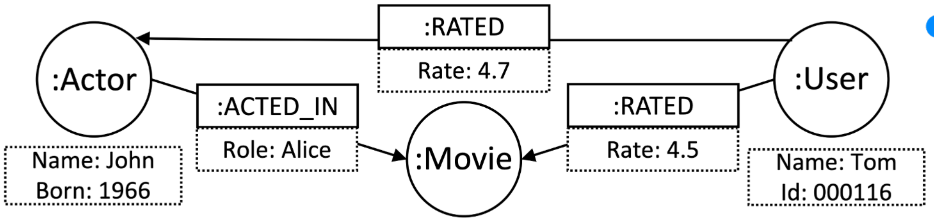
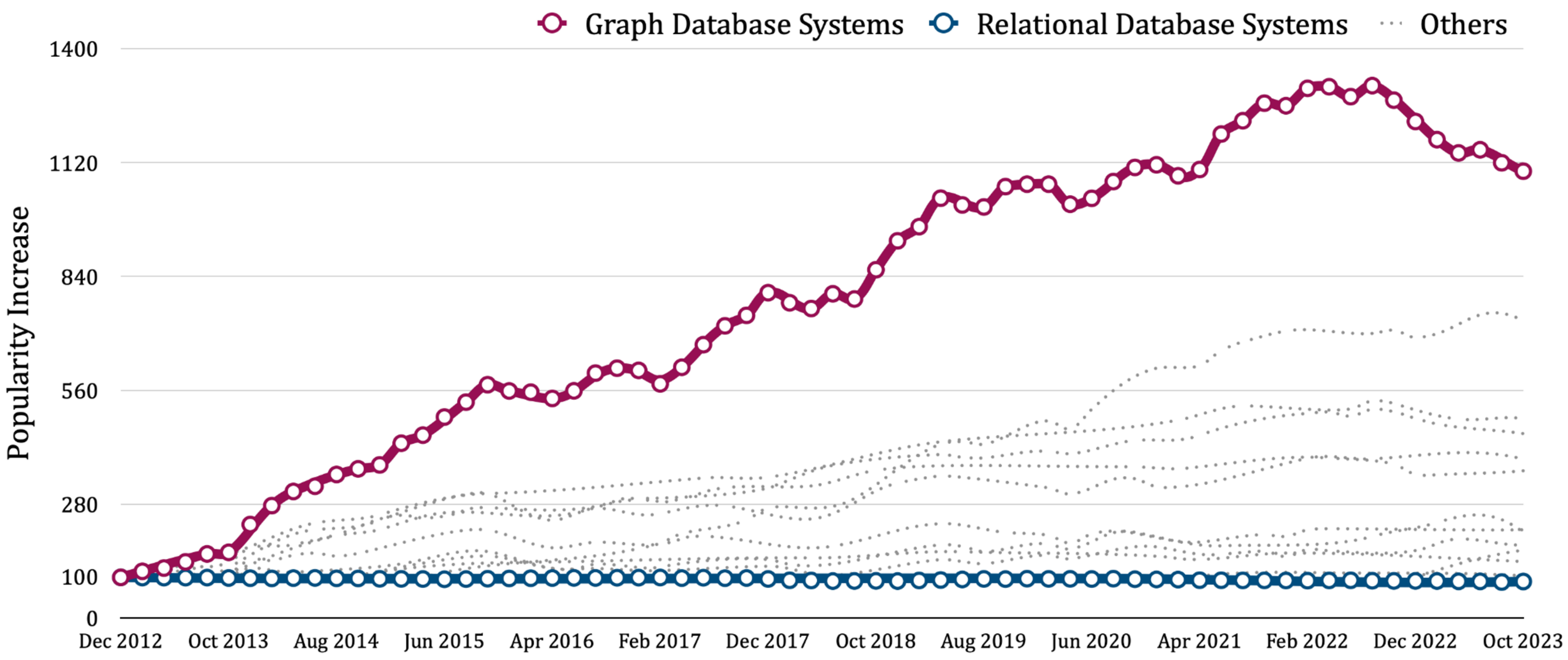


neo4j · JanusGraph · Apache TinkerPop · AGENS Graph Database

The Fastest Growing Model in Past Decade*



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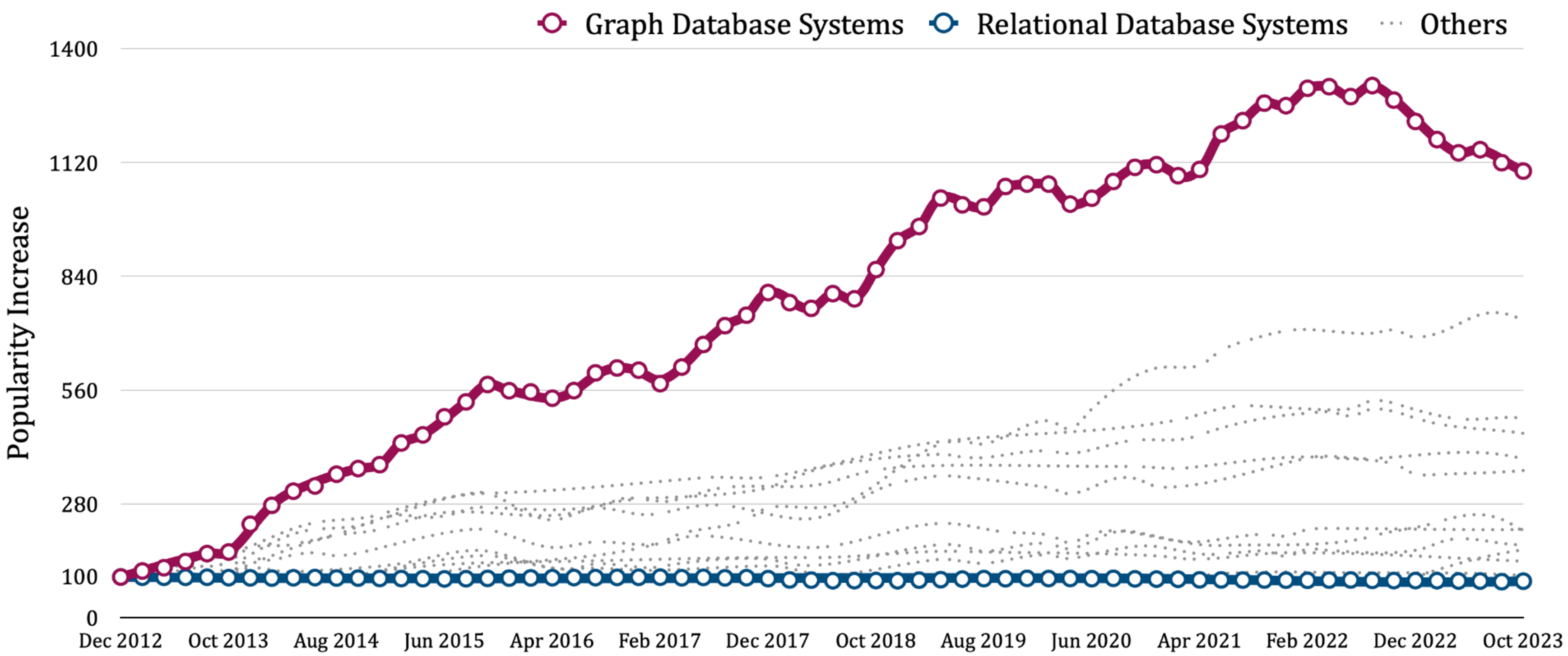

Graph Database Testing becomes essential to improve Robustness and Accuracy

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Internal Errors (Crash): out of service (segfault, unexpected exception)

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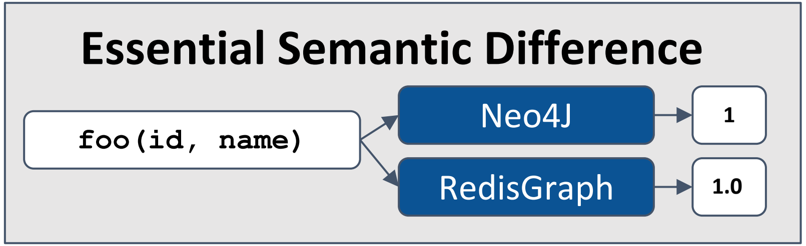

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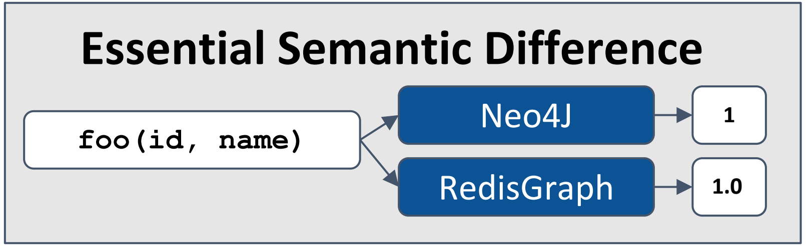

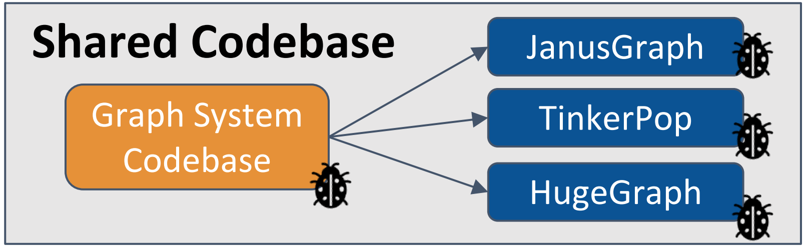

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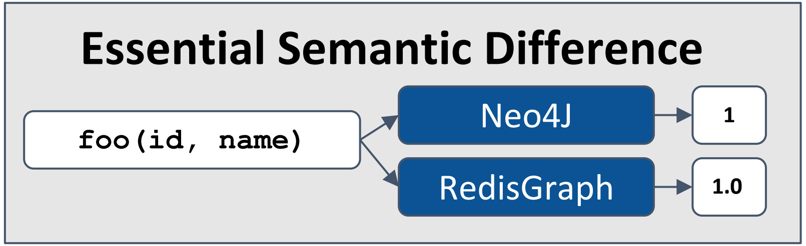

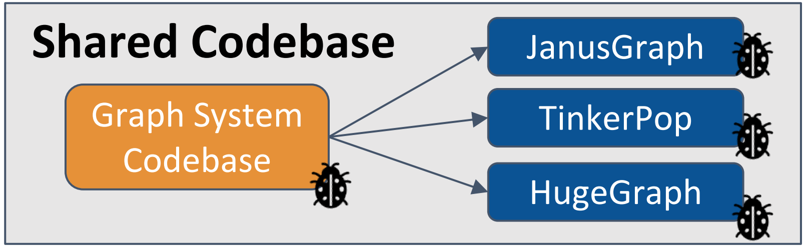

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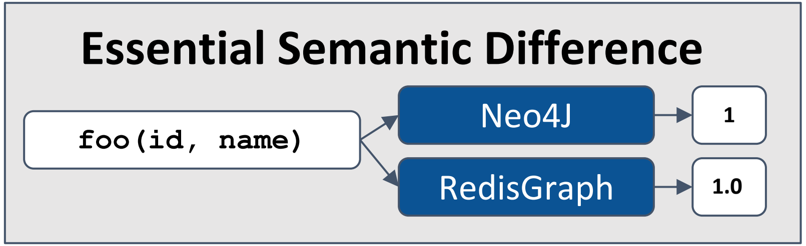

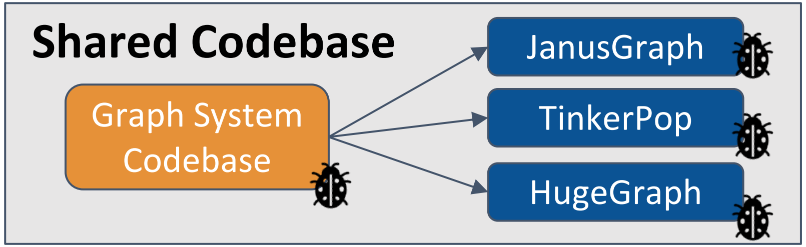

GDBMeter (ISSTA'23): metamorphic testing (TLP*)

- focus on mutating **predicates** (constraints)

GDBMeter

*: Ternary Logic Partitioning (TLP) splits predicate *P* into three possible outcomes: *True*, *False*, or *Null*.

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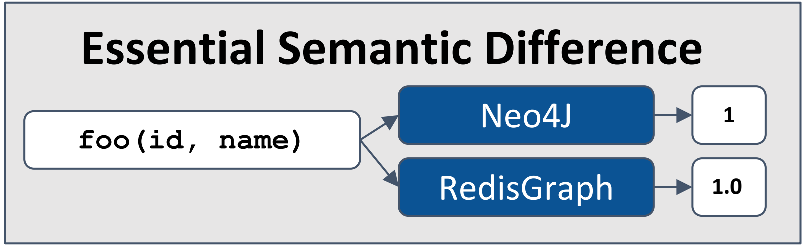

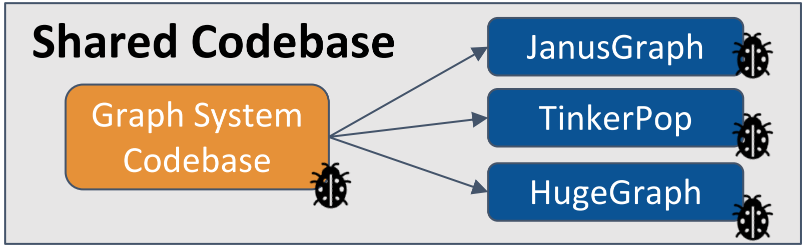

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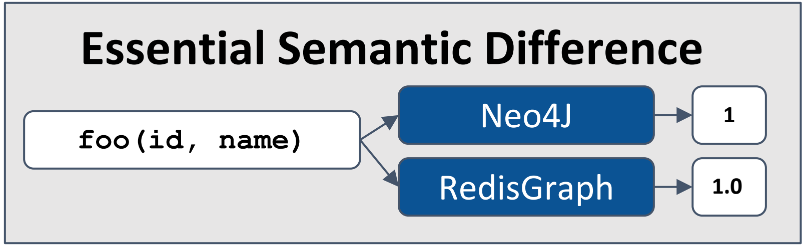

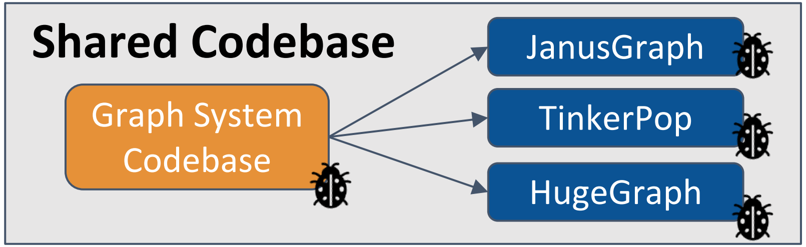

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Why? Have we considered all features in graph queries?

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Consider Graph When Testing Graph

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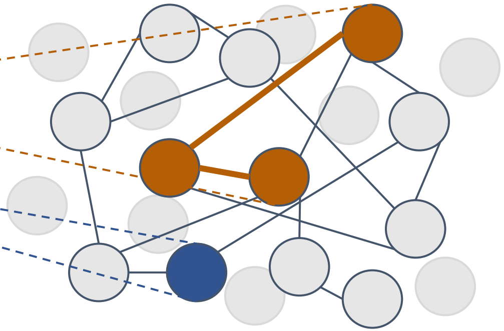

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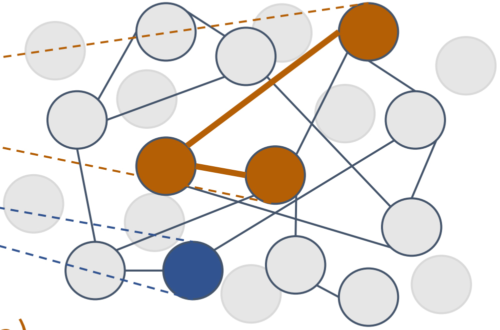

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Graph Query: **graph patterns** + predicates + others

Additional Constraints in Graph Queries

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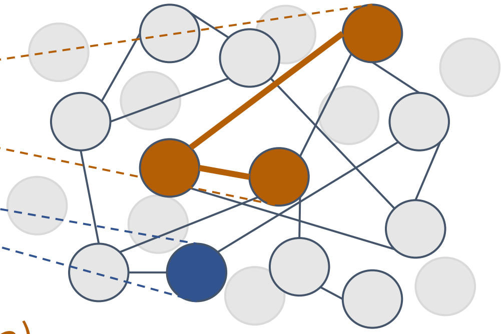

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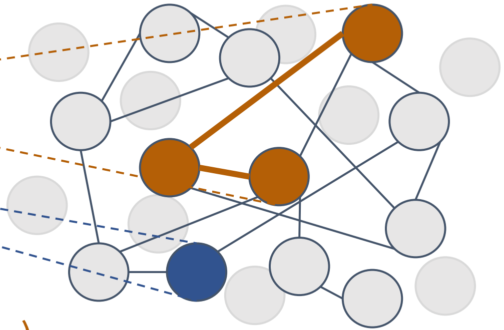

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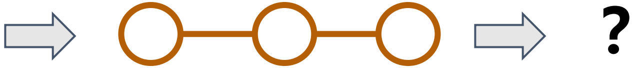
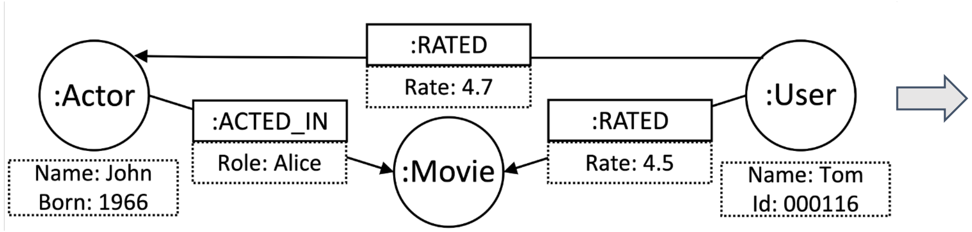
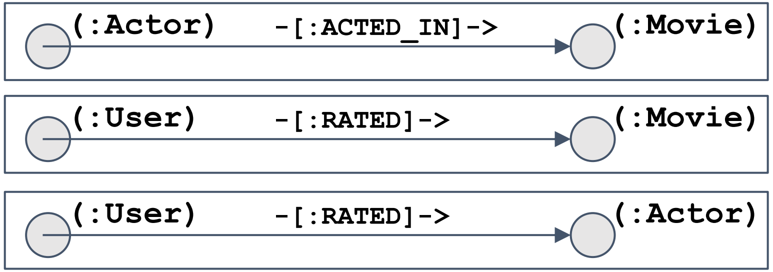
How to systematically mutate Graph Patterns?

(a)--(b)--(c)



From Graph to Directed Edge Sets





Directed Edge Sets: edges with their heads, tails, and edges information

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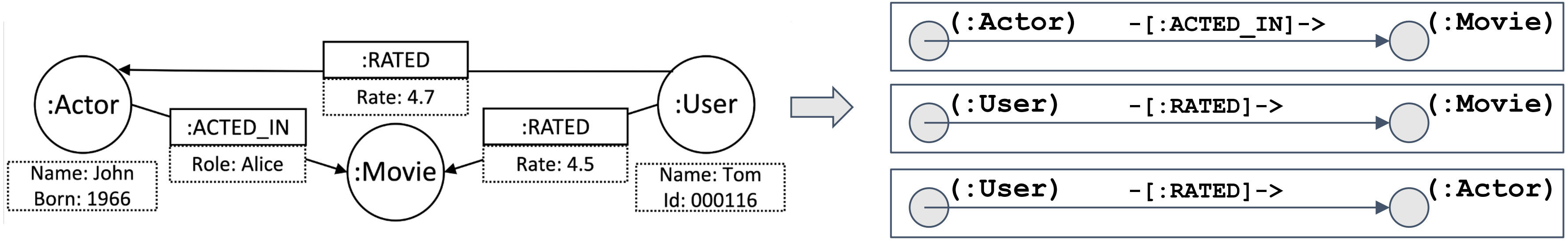

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Graph Query Mutation ⇨ Graph Pattern Mutation ⇨ Sets Mapping

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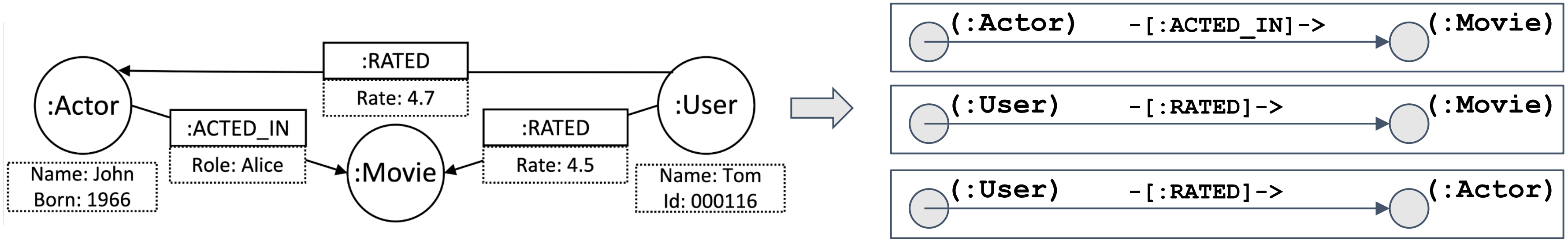

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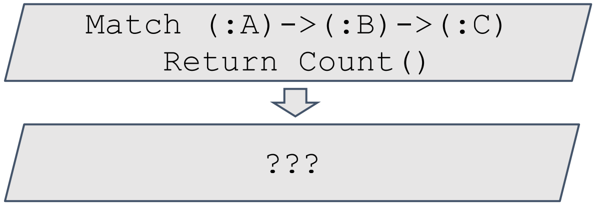

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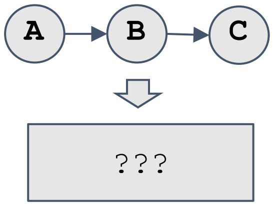

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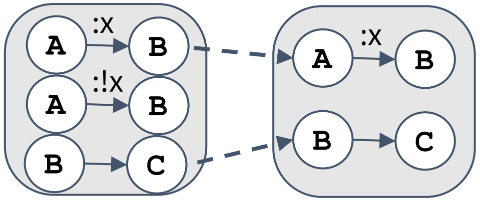

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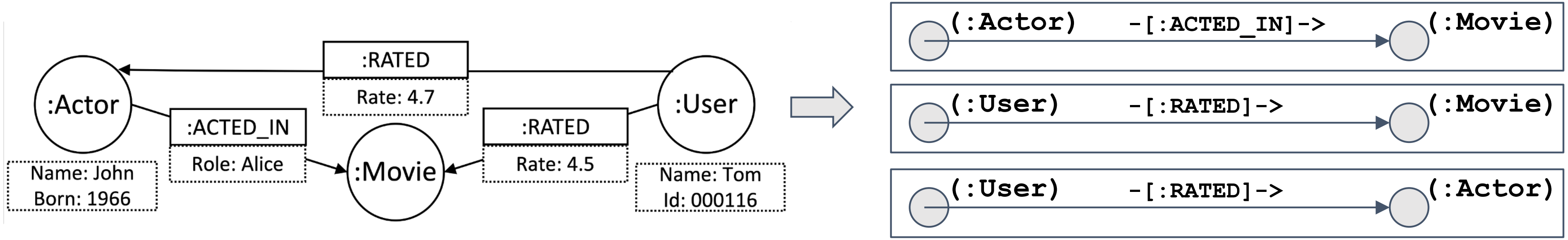

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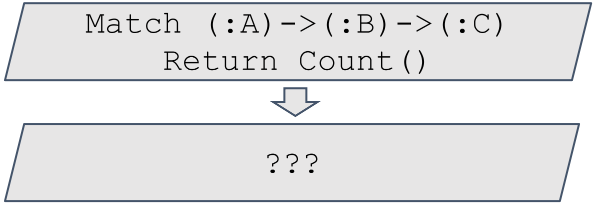

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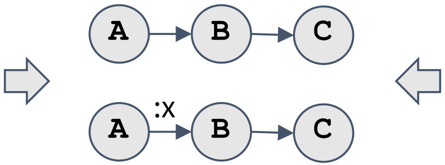

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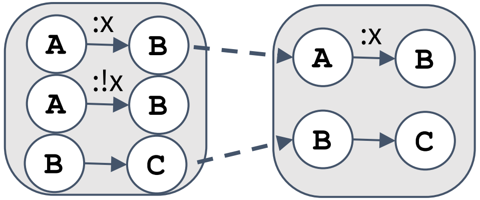

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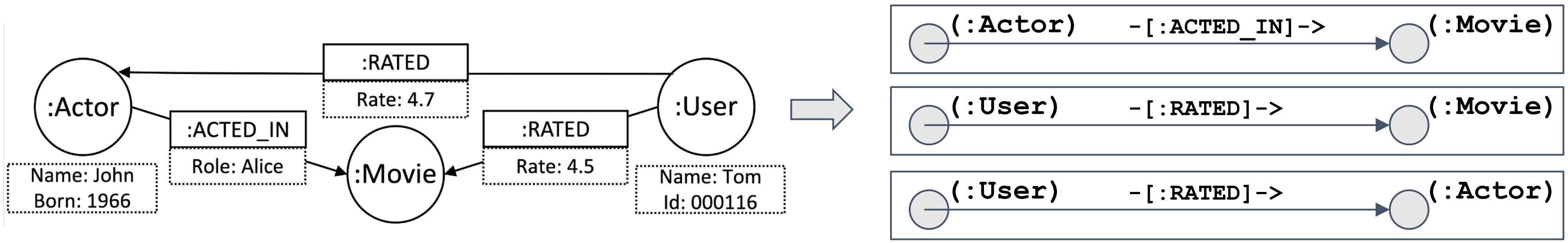

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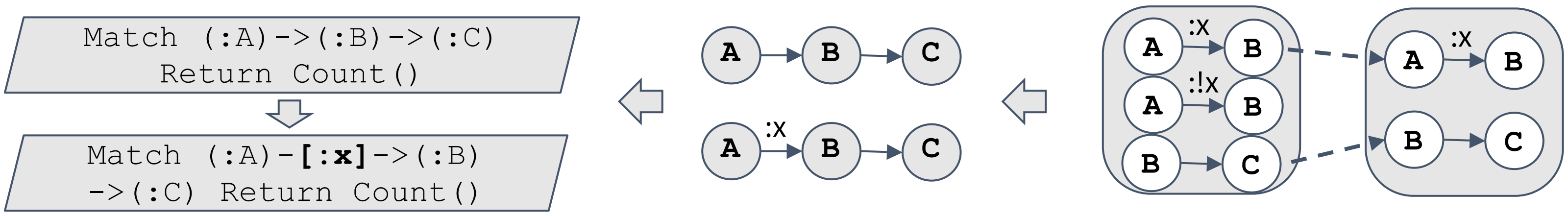

Restricted Query Mutation **Restricted Pattern Mutation** **Injective Mapping**

GraphGenie*:

first metamorphic testing approach considering graph pattern mutations

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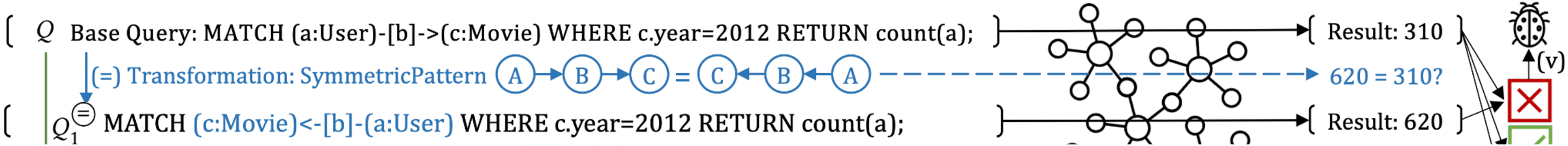

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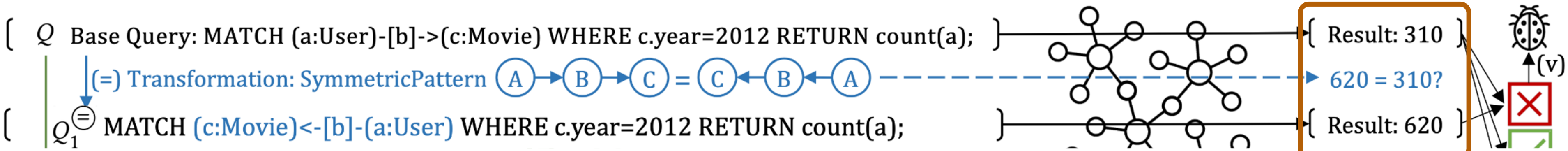
test oracle!



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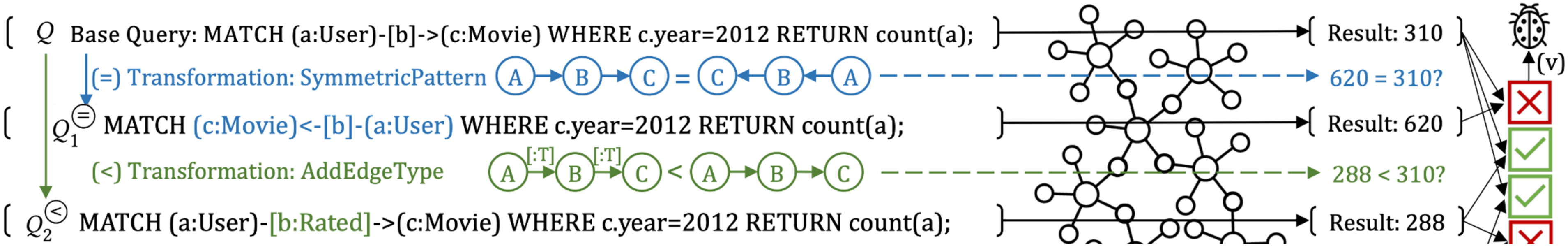

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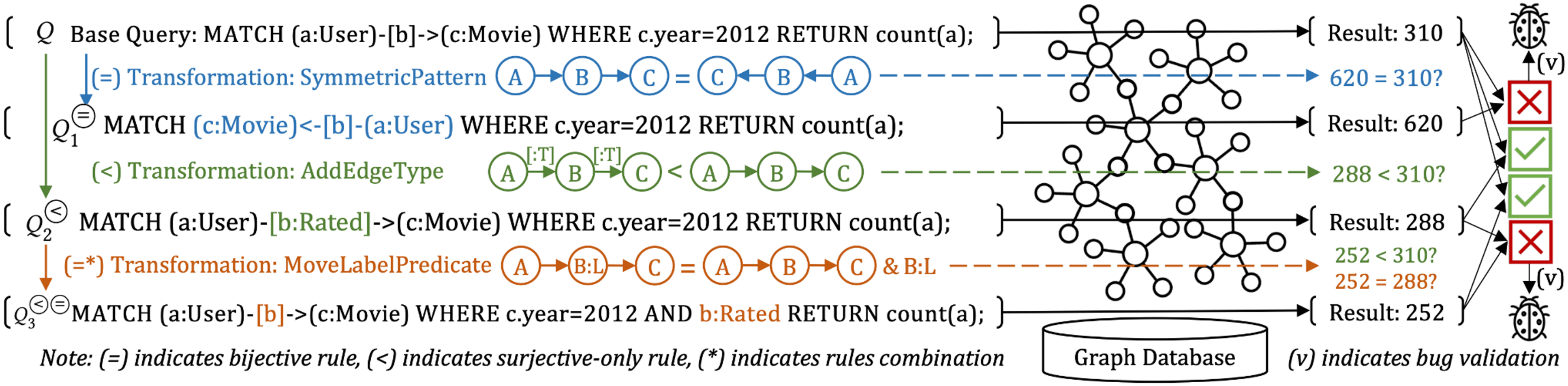

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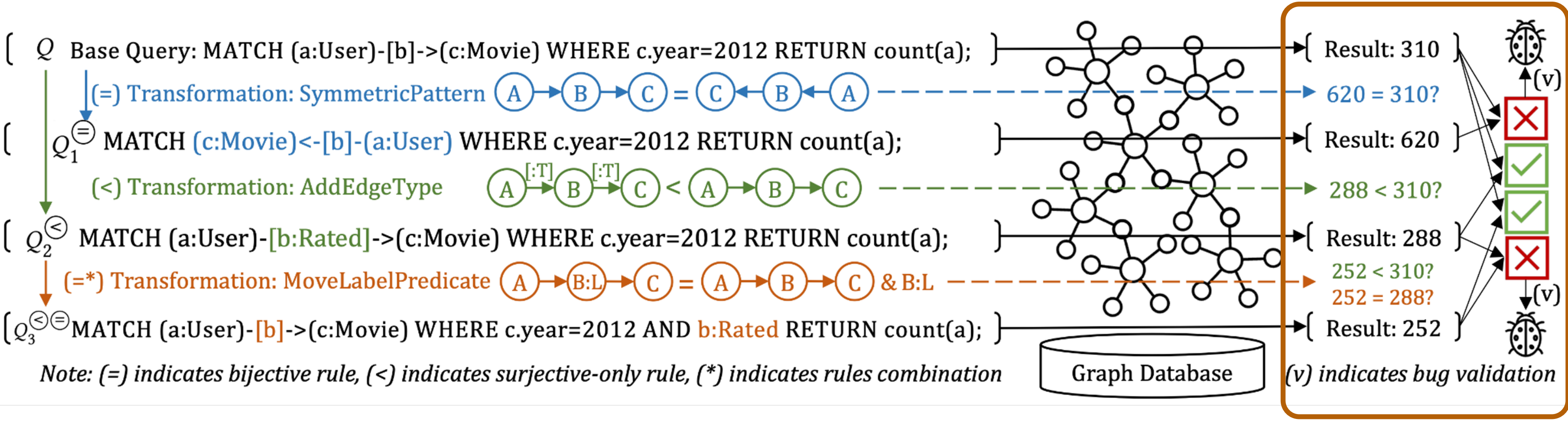

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Graph Query Transformations (GQT)

- ◐ Structure-GQT: mutations considering Graph patterns
- ◑ Property-GQT: mutations considering Graph properties
- ○ Non-GQT: mutations on other parts of graph queries

ID	Rule Name	Class	Type	Transformation	Example (In *Cypher*)
01	SymmetricPattern	◐	Equivalent	Replace graph pattern with a symmetric one	MATCH (A~~:MOVIE~~)--(B:MOVIE) RETURN COUNT(~~A~~B);
02	UnfoldCyclicPattern	◐	Equivalent	Unfold cyclic pattern via adding predicate	MATCH (A)--(B:MOVIE)--(C~~A~~) WHERE A=C RETURN COUNT(A);
03	PatternPartition	◐	Equivalent	Split graph pattern to disjoint sub-patterns	MATCH (A)-->(B:MOVIE), (B:MOVIE)-->(C) RETURN COUNT(A);
04	AddEdgeDirection	◐	Variant	Add edge direction to undirected edge	MATCH (A)-->(B:MOVIE) WHERE B.YEAR=2012 RETURN COUNT(A);
05	SpanningSubgraph	◐	Variant	Spanning subgraph by deleting edges	MATCH (A)-->(B:MOVIE)-->(C)~~, (A)-->(C)~~ RETURN COUNT(A);
06	InducedSubgraph	◐	Variant	Induced subgraph by deleting vertices	MATCH (A)--(B:MOVIE)--(C)~~--(D:ACTOR)~~ RETURN COUNT(A);
07	ExpandPattern	◐	Variant	Expand graph pattern by adding nodes	MATCH (A)--(B:MOVIE)--(C:MOVIE)--(D) RETURN COUNT(A);
08	AddNodeLabel	◑	Variant	Add node label to existing node	MATCH (A:USER)--(B:MOVIE) WHERE NOT A=B RETURN COUNT(A);
09	AddEdgeType	◑	Variant	Add edge type to existing edge	MATCH (A:USER)-[R:RATED]-(B:MOVIE) RETURN COUNT(A);
10	MoveLabelPredicate	◑	Equivalent	Move node label to the predicate	MATCH (A~~:USER~~)--(B:MOVIE) WHERE A:USER RETURN COUNT(A);
11	CountIdProperty	◑	Equivalent	Count the node id property	MATCH (A:USER)--(B:MOVIE)-->(C) RETURN COUNT(ID(A));
12	CountOtherName	◑	Equivalent	Count other name in the same path	MATCH (A:USER)--(B:MOVIE)-->(C) RETURN COUNT(~~A~~C);
13	DisjointPredicate	○	Equivalent	Split predicate into disjoint parts	MATCH (A) WHERE A.P>0 ~~AND~~WITH * WHERE A.Q>0 COUNT(A);
14	RedundantPredicate	○	Equivalent	Append alway-true condition to predicate	MATCH (A:USER)–(B:MOVIE) WHERE NOT A=B RETURN COUNT(A);
15	RenameVariables	○	Equivalent	Rename node or edge variables	MATCH (~~A~~N)--(~~B~~M:MOVIE) WHERE ~~A~~N:USER RETURN COUNT(~~A~~N);
16	AddCallWrapper	○	Equivalent	Return results by calling the function	CALL { MATCH (A:USER) RETURN COUNT(A) AS X } RETURN X;

Effectiveness

Effectiveness in discovering unknown bugs in mature graph database systems?

	Logic Bugs			Internal Errors	
GDBMS	Unconfirmed	Confirmed	Fixed	Fixed	Total
Neo4j	0	0	2	3	5
RedisGraph	1	3	1	0	5
AgensGraph	0	0	3	0	3
Gremlin-DBs	6	0	0	0	6
Total	7	3	6	3	19

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Logic Bug via Symmetric Pattern in RedisGraph

Q: `MATCH (a:A)-[*1..2]-(b:B) return count(1);`
`// Result: 204    Response Time: 0.76ms`
$Q^{⊜}$: `MATCH (b:B)-[*1..2]-(a:A) return count(1);`
`// Result: 238    Response Time: 0.75ms`

https://github.com/RedisGraph/RedisGraph/issues/2865

Graph Pattern: variable length patterns having endpoints with (a:A) and (b:B)

Fixed. Caused by incorrect logic to stop expanding a path upon detecting a cycle.

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	Logic Bugs			Internal Errors	
GDBMS	Unconfirmed	Confirmed	Fixed	Fixed	Total
Neo4j	0	0	2	3	5
RedisGraph	1	3	1	0	5
AgensGraph	0	0	3	0	3
Gremlin-DBs	6	0	0	0	6
Total	7	3	6	3	19

Effectiveness in discovering unknown bugs in mature graph database systems?

Logic Bug via Symmetric Pattern in RedisGraph

```
Q: MATCH (a:A)-[*1..2]-(b:B) return count(1);
    // Result: 204    Response Time: 0.76ms
Q⊜: MATCH (b:B)-[*1..2]-(a:A) return count(1);
    // Result: 238    Response Time: 0.75ms
```

https://github.com/RedisGraph/RedisGraph/issues/2865

Graph Pattern: variable length patterns having endpoints with (a:A) and (b:B)

Fixed. Caused by incorrect logic to stop expanding a path upon detecting a cycle.

Graph Pattern: partition the pattern (a)->(b) into two paths (a) and (a)->(b)

Fixed. Caused by columns not visible when involving variable length edge

Logic Bug via Pattern Partition in AgensGraph

```
Q: MATCH (a)-[*1..1]->(b) RETURN count(a);
    // Result: 100
Q⊜: MATCH (a),(a)-[*1..1]->(b) RETURN count(a);
    // ERROR:  column "a" does not exist
```

https://github.com/bitnine-oss/agensgraph/issues/609

Improvement via **Graph Patterns**

Q:
```
MATCH (a)-[]-(a) RETURN count(a);
    // Base Query Result: 200
MATCH (a)-[]-(a) WHERE id(a)>=1.0 RETURN count(a);
    // (TLP-True) Result: 200
MATCH (a)-[]-(a) WHERE NOT id(a)>=1.0 RETURN count(a);
    // (TLP-False) Result: 0
MATCH (a)-[]-(a) WHERE id(a)>=1.0 IS NULL RETURN count(a);
    // (TLP-Null) Result: 0
```
$Q^{⊜}$:
```
MATCH (a)-[]-(b) WHERE a=b RETURN count(a);
    // (GraphGenie) Result: 16
```

GDBMeter

We analyze fixed bugs found by us and use GDBMeter's approach to detect them. **Out of 9 bugs that are applicable to Ternary Logic Partition, GDBMeter was able to detect only 3 bugs.**

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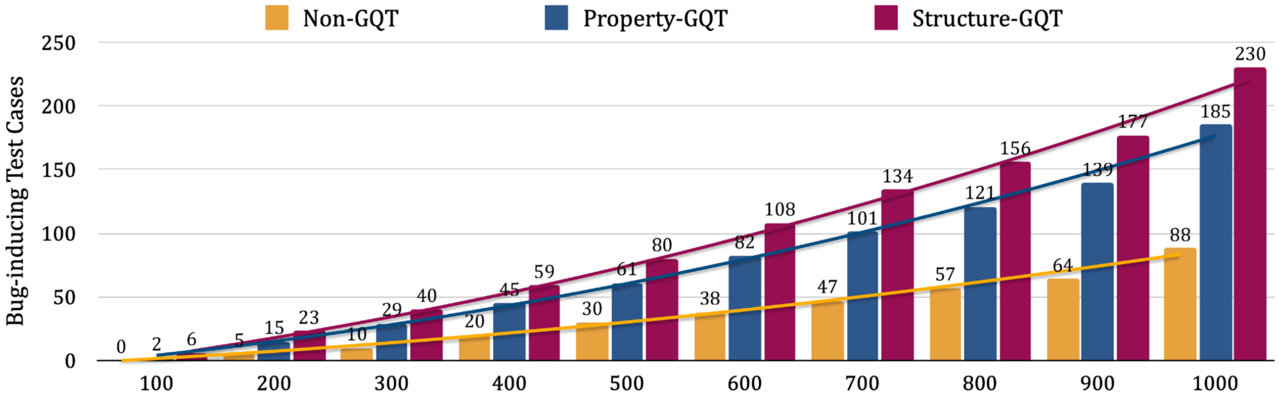
Non-GQT rules are effective in finding bug-inducing test cases while **using GQT rules facilitates uncovering more bug-inducing cases in testing GDBMS.**



Finding Performance Issues

Graph Query Transformations:

We reuse transformations for logic bugs, then redesign the test oracles

Test Oracle (e.g. for equivalent mutated queries):

The difference of execution time should be less than the threshold T[=].

$$max(time(Q), time(Q^{\boxed{=}})) \leq min(time(Q), time(Q^{\boxed{=}})) \times T^{\boxed{=}}$$

(T[=] is customizable, we set it as **5x**)

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Performance Issues found in Neo4J

Bug ID	Status	Time(Q)	Time(Q')	Developer Feedback
12973	Fixed	4642011ms	5984ms	A fix will come with the next release
13034	Fixed	100ms	201384ms	A fix will come with the next release
13010	Confirmed	77ms	12147ms	Bad plan but low priority to optimize
12957	Confirmed	13933ms	22ms	A suboptimal plan in old version
13003	Intended	165547ms	332ms	Query plan is suboptimal but intended
13033	Intended	1402ms	16585ms	Inaccurate estimated rows and bad plan

Thank You!

Check Our Paper:

https://yuanchengjiang.github.io/docs/GraphGenie-ICSE24.pdf

Try GraphGenie:

https://github.com/YuanchengJiang/GraphGenie

NUS National University of Singapore