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Dynamic Symbolic Database Application Testing

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Motivation

Maximizing code coverage is an important goal in testing.

- Database applications: input can be user-supplied queries.
- Query results will be used as program values in program logic.
- Different queries thus result in different execution paths.
- To maximize code coverage: we need to enumerate queries in an effective way.

Our Method

Generate queries dynamically by inverting branching conditions in existing program execution paths.

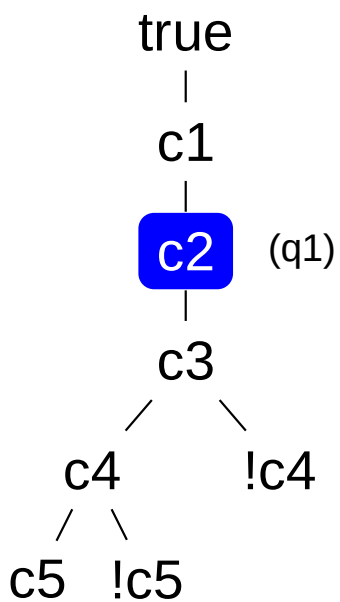
1. Monitor the program's execution paths by *dynamic symbolic execution* (e.g., Dart, Pex).
2. Invert a branching condition on some covered path $\rightarrow$ a new test query.
3. Execute the query, bring in new tuples.
4. The new tuples will cover new paths.
5. Do 1-4 iteratively.

Illustration of the Idea

After the initial query

$q_1 = c_1 \wedge c_2$

Execution tree (maintained by dynamic symbolic engine):
each path to a leaf node represents an execution path, encountered for tuples satisfying the branching conditions on the path.




```
if (z > 0) {          // c1
    if (z < 100)      // c2
        // ..
}
```

Illustration of the Idea

After the initial query, the candidate queries

Each dashed edge represents an inversed branching condition, thus a candidate query.

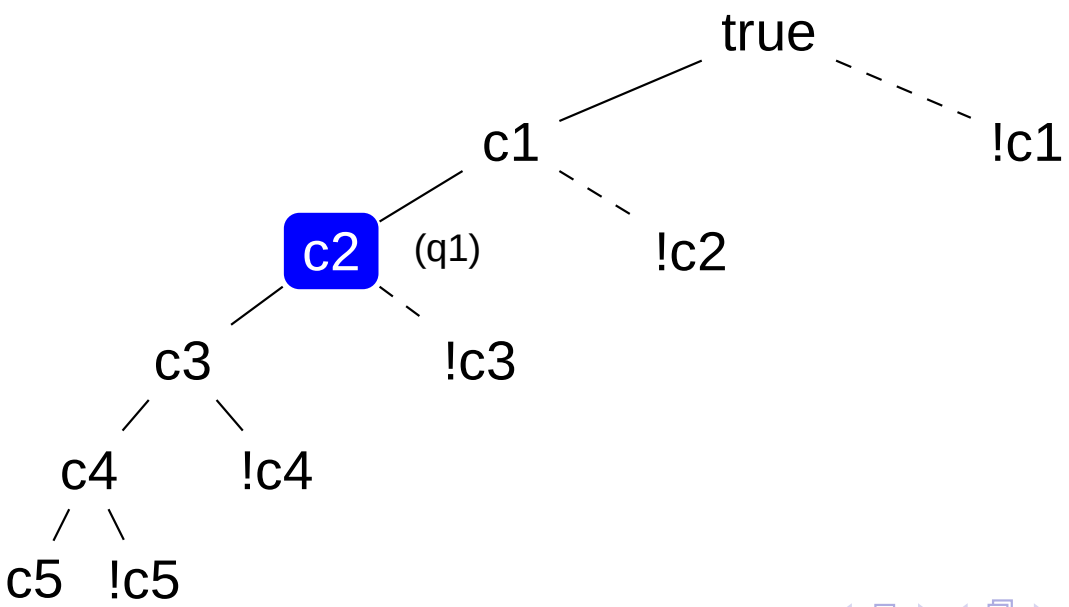


Illustration of the Idea

The second test query

q_2=!c_1

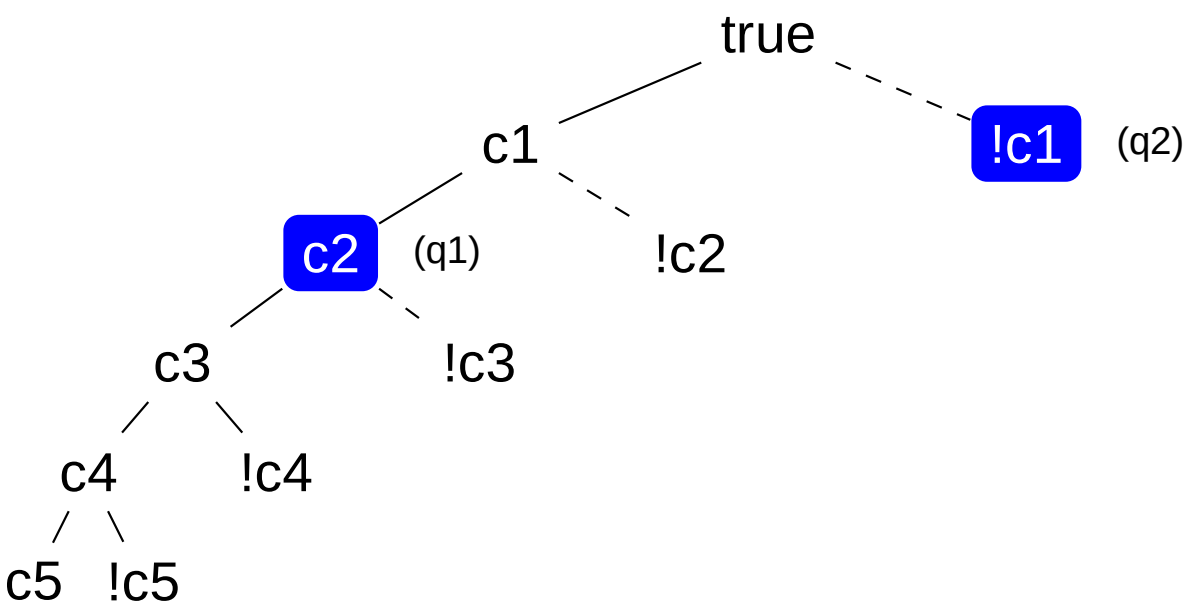


Illustration of the Idea

After the second test query

q_2=!c_1
candidate queries are again dashed.

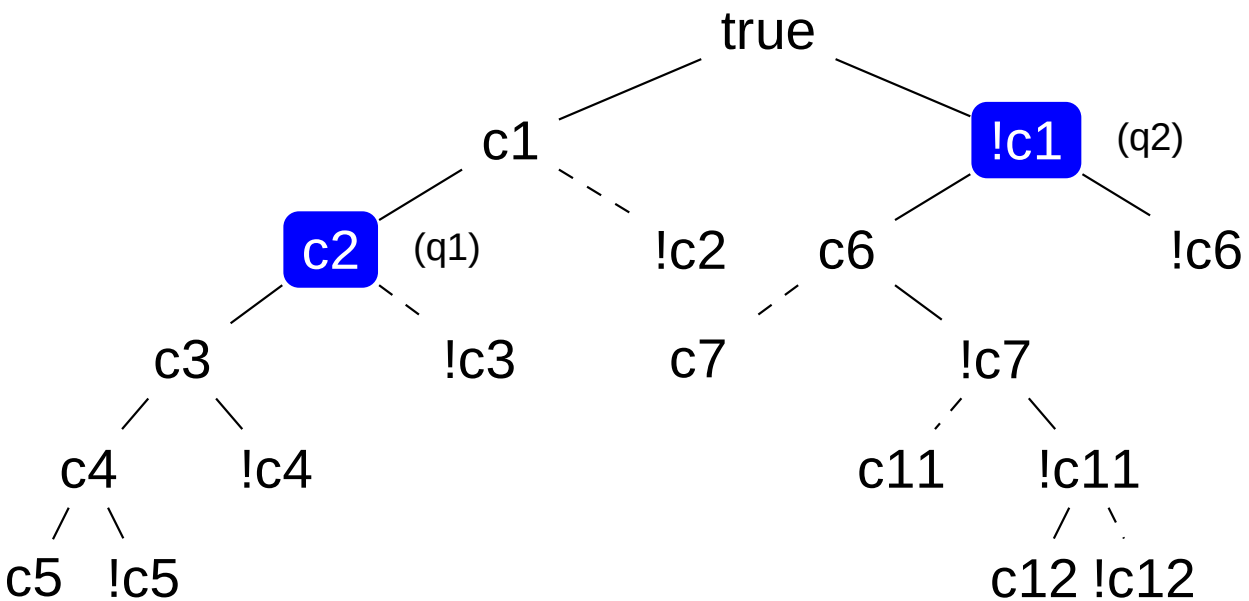


Illustration of the Idea

The third test query

$q_3 = !c_1 \wedge c_6 \wedge c_7$

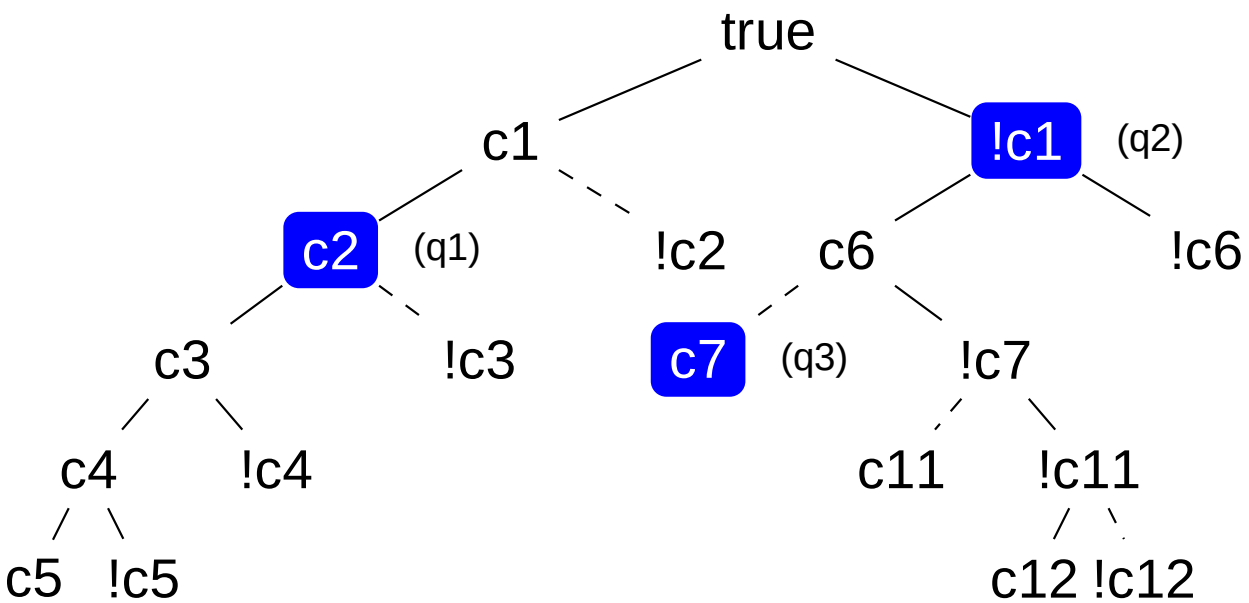


Illustration of the Idea

After the third test query

$q_3 = !c_1 \wedge c_6 \wedge c_7$

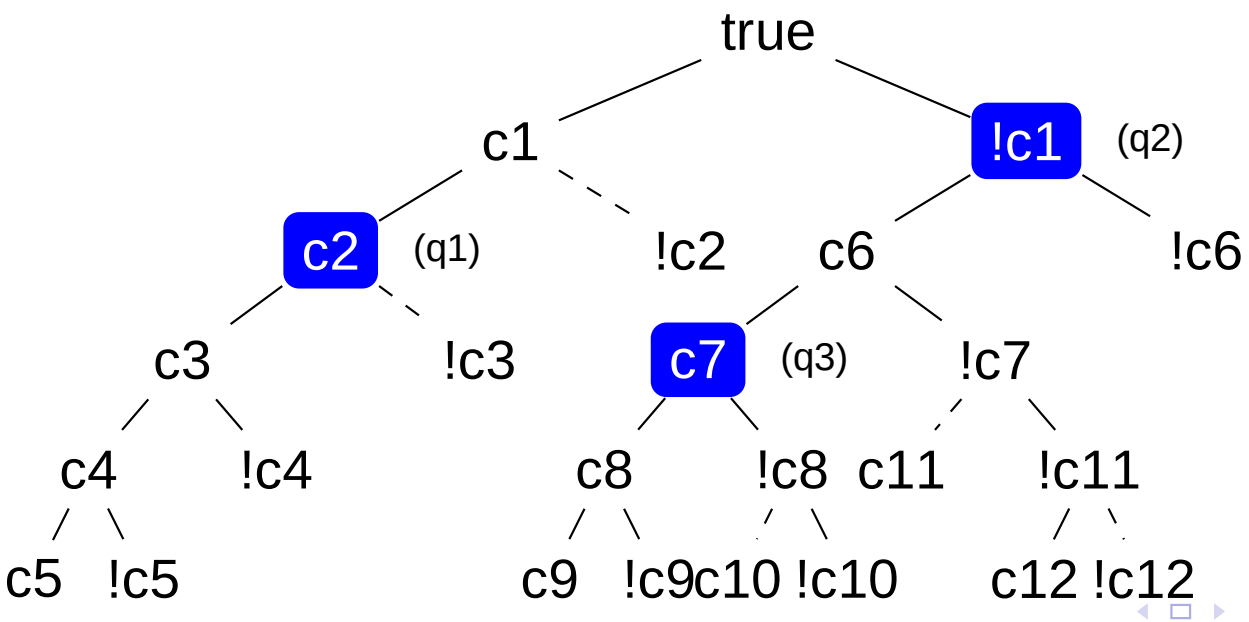


Illustration of the Idea

The fourth test query

$q_4 = !c_1 \wedge c_6 \wedge !c_7 \wedge !c_{11} \wedge !c_{12}$

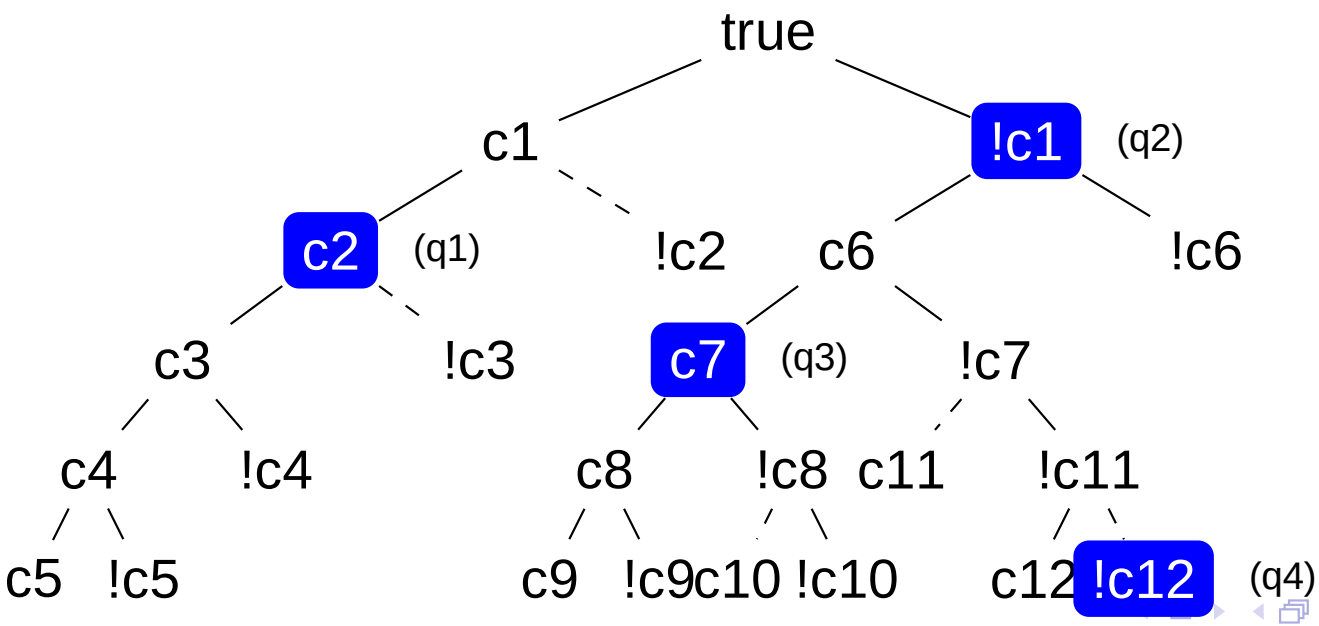
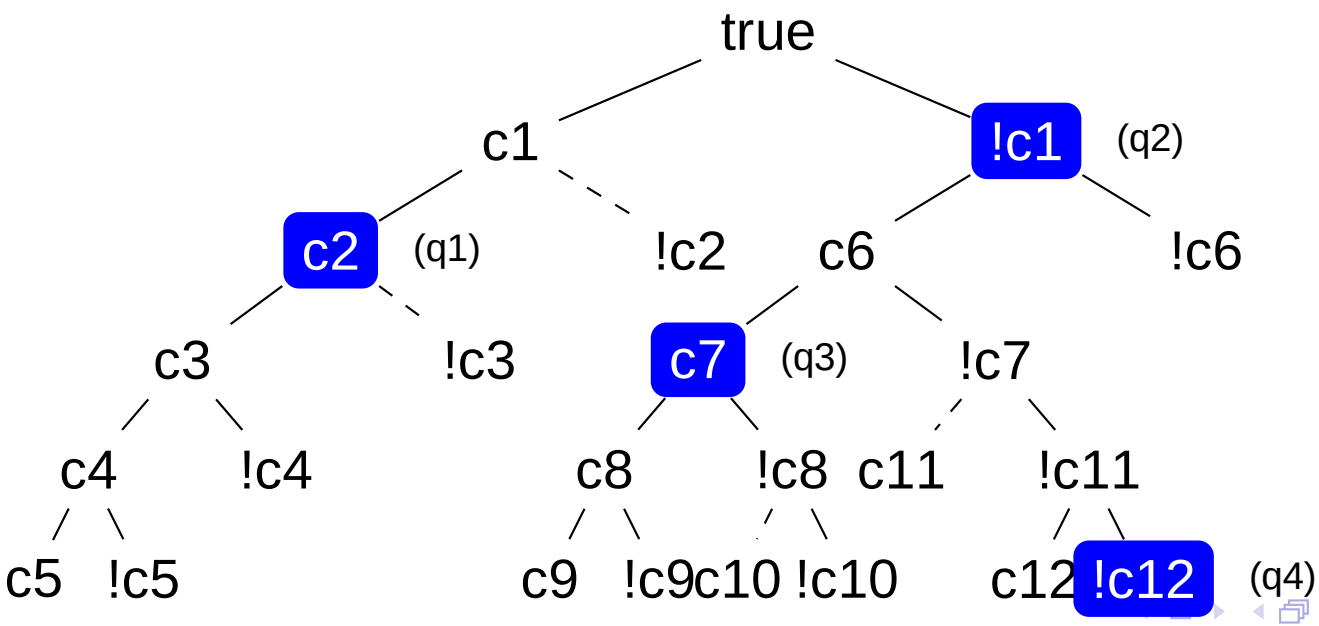


Illustration of the Idea

After the fourth test query

$q_4 = !c_1 \wedge c_6 \wedge !c_7 \wedge !c_{11} \wedge !c_{12}$



Advantages of the Proposed Method

- Real data, no mock database (which can be hard to generate).
- No need to worry about if the mock database is representative.
- Given large space of possible program paths, we only test those that can be encountered for real data.
- This is especially useful for applications that only read existing data.

Alternative Method 1: Brute force

Test for every tuple in database.

- Too costly
  - Limited resources in testing.
  - Many tuples result in the same execution path. Thus efforts wasted.
- May not be possible to get all the tuples
  - Security constraint.
  - Query capability constraint. (e.g., deep-Web databases)

Alternative Method 2: Sample the existing database

Do sampling first, then test for every tuple in the sample.

- A presentative database sample may not trigger a set of program execution paths that is representative of the paths encountered in production use.
- E.g., a column with 1 million distinct values; several particular values will trigger some paths.
- Ours can be viewed as a sampling technique that is aware of the program structure.

Alternative Method 3: Generate custom mock databases

Generate a mock database such that its data will expose a bug in the program

- Will expose potential program bugs.
- But users may not care about them.
- Because many “bugs” will never occur in practice.
- Because the mock database generator typically cannot generate fully realistic databases.

Alternative Method 4: Static Analysis

Static program analysis is typically:

(+) Fast
(-) Imprecise: misses bugs and gives false alarms

Our approach: Test = execute the program (dynamic analysis)

(+) Fully precise: no false alarms
(-) Resource-hungry, will still miss bugs

Our (dynamic) analysis reasons about program + existing database contents. We are not aware of any static analysis that does that.

Assumptions/Limitations

Queries

- single-relation conjunctive selection query.
- Each conjunct is $a \odot v$, where a is an attribute, v is a constant value, and $\odot$ can be $<$, $\leq$, $>$, $\geq$, $=$, or $\neq$.
- no grouping, aggregation, join, insertion, deletion, updates.

Programs

- follow tuple-wise semantics.
- if a branching condition depends on a database tuple, the condition can be rewritten to the same form of the query conjuncts: $a \odot v$.

Iterative Testing Method

1: $q \leftarrow$ define an initial test query; $\mathcal{Q} \leftarrow \{q\}$
2: **repeat**
3: $\quad \mathcal{T} \leftarrow$ run q and get the first n_q result tuples
4: $\quad$ **for** each tuple t in $\mathcal{T}$ **do**
5: $\quad\quad$ run the program over t and update the execution tree $tree_{\mathcal{Q}}$ with encountered new execution paths
6: $\quad \overline{tree_{\mathcal{Q}}} \leftarrow$ the complement tree of $tree_{\mathcal{Q}}$
7: $\quad \mathcal{Q}_c \leftarrow$ get the candidate queries based on $\overline{tree_{\mathcal{Q}}}$
8: $\quad q \leftarrow$ select a query from $\mathcal{Q}_c$
9: $\quad \mathcal{Q} \leftarrow \mathcal{Q} \cup \{q\}$
10: **until** stopping criteria satisfied

Challenges

How to

- decide how many tuples to retrieve for a query?
- choose the next test query?
- design stopping condition for testing?

Optimization Goals

Given program $\mathcal{P}$ and a set of test queries $\mathcal{Q}=\{q_i\}$

maximize coverage

$Path(\mathcal{P},\mathcal{R},\mathcal{Q}) = \{Path_t | t \in \bigcup_{\mathcal{T}_i}\}$, where $\mathcal{T}_i$ is the first n_i tuples for query q_i.

minimize cost

$cost(\mathcal{Q}) = \sum_i cost(q_i)$
$cost(q_i) = q\_cost(q_i) + t\_cost(q_i) = w + c \times n_i + t \times n_i$

- t_cost: t is test cost per tuple.
- q_cost: w is query cost to get first result tuple, c is query cost to get each additional tuple.

Why only n_i tuples for a query q_i?

Multiple tuples will result in the same program execution path. After a certain number of initial tuples, most or all distinct paths may have been encountered.

Less retrieved/tested tuples means both less testing cost and less query execution cost.

How to choose next q and n

Greedy Approach

Given candidate query q,

$$score(q) = \frac{cost'(q)}{|Path'(\mathcal{P},\mathcal{R},\mathcal{M},\mathcal{Q}\cup\{q\})|-|Path(\mathcal{P},\mathcal{R},\mathcal{M},\mathcal{Q})|}$$

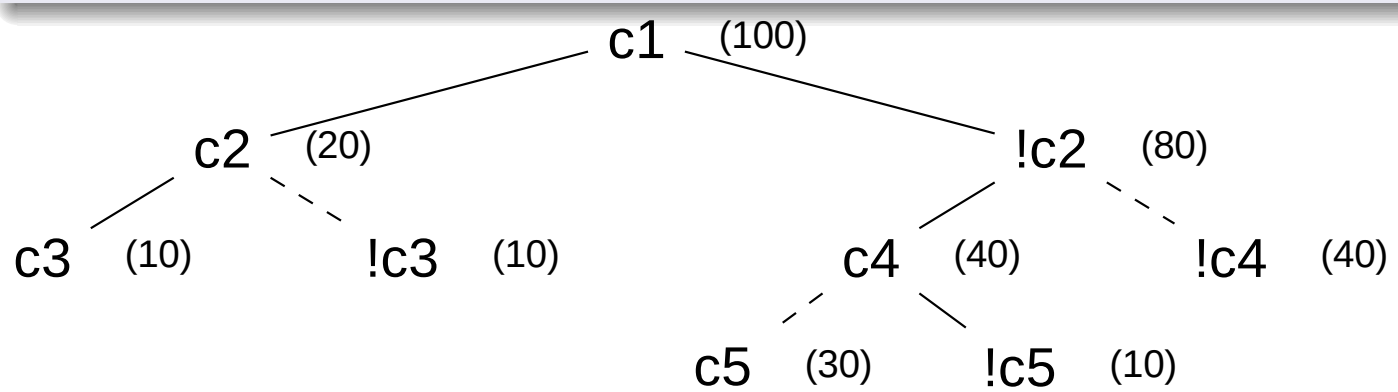
$|Path'(\mathcal{P},\mathcal{R},\mathcal{M},\mathcal{Q}\cup\{q\})|$: estimate of $|Path(\mathcal{P},\mathcal{R},\mathcal{M},\mathcal{Q}\cup\{q\})|$
$cost'(q)$: estimate of $cost(q)$
(both are functions of n)

find q that minimizes $score(q)$

Estimating the Coverage and Cost

Estimating the Coverage

- Estimate the query result size of leaf node (query).
- The result sizes for intermediate nodes are accumulated.



Estimating the Cost

- both initial tuple cost and total cost.

EXPLAIN (supported by major DBMSs)

Stopping Condition for Testing

- testing resource limit reached
- no more candidate queries
- no candidate query can return non-empty result
- total number of encountered tuples (associated with distinct paths) equals the table size

Implementation

Overview

- Fully automated tool
- Analyze Java bytecode programs (any Java program, no need for source code)
- Rewrite application bytecode at load-time: after each application bytecode instruction, insert a call to our dynamic symbolic engine
- Use inserted calls to maintain an accurate symbolic representation of program state
- Treat calls to database (e.g., Jdbc) differently: Represent returned values as symbolic variables and track how the program uses them, i.e., in path conditions

Implementation

Details

- Use Java 5 instrumentation facilities
- Use third-party open source bytecode instrumentation framework ASM
- Implement on top of new dynamic symbolic engine Dsc:
- Allows handling of regular (non-query) program inputs
- Solve constraints on regular program inputs with powerful third-party satisfiability modulo theories (SMT) constraint solver Z3

Ongoing and Future Work

Several directions

- Finish prototype implementation
- Evaluate on realistic applications
- Compare with mock-database generation techniques + compare with traditional database sampling techniques:
- Can we achieve higher coverage of the application code that is reachable with the existing database contents?
- How to deal with database insert, update, delete?

Thank you!

Contact

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References

Dynamic Symbolic Execution Systems

- Dart: C programs, by Godefroid et al. [PLDI'05]
- jCute: Java programs, by Sen et al. [CAV'06]
- Klee: C programs, by Cadar et al. [OSDI'08]
- Pex: .Net programs (C#, etc.), by Tillmann et al. [TAP'08]

Database application testing via mock database generation

- jCute extension: Java programs, by Emmi et al. [ISSTA'07]
- Qex (Pex extension): .Net programs (C#, etc.), by Veanes et al. [ICFEM'09]

References

Main tools used by our prototype implementation

- ASM: http://asm.ow2.org/
- Z3: http://research.microsoft.com/en-us/um/redmond/projects/z3/