assertion-driven analyses

from compile-time checking to runtime error recovery

sarfraz khurshid
the university of texas at austin

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overview

programmers have long used assertions

- runtime checks
- documentation

assertions **are** lightweight specifications

- written using the underlying programming language

we envision a much broader use of assertions

- developers assert designs
- static analyses check conformance to designs
- systematic approaches test executable code
- runtime checks monitor for erroneous executions
- error recovery repairs as desired

assertion-based repair [elkarablieh et al ASE'07]

an assertion violation indicates a corrupt program state

traditional approach to handle an assertion violation:

1. terminate the program
2. debug it (if possible) and re-execute it

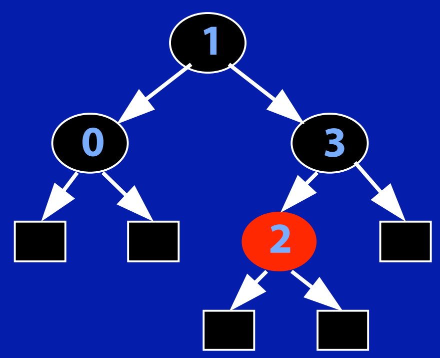
at times however, terminate/debug/re-boot may not be feasible, e.g., when persistent data is corrupted

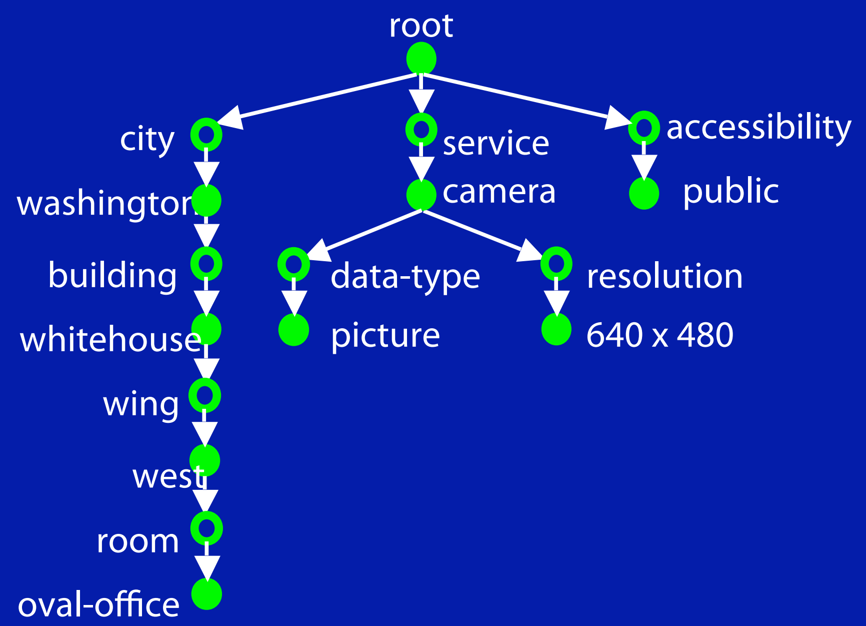
our approach to handle a violation:

1. **repair** the state of the program
2. let it continue to execute

repair tries to bring the system/data in an acceptable state (possibly without re-booting) to continue execution

examples of structurally complex data





structural integrity constraints

violation of integrity constraints is a likely form of corruption

assertions readily express complex constraints

- e.g., a graph traversal that checks for acyclicity

in OO programs, **repOk** predicates express class invariants

- good programming practice advocates writing repOk's

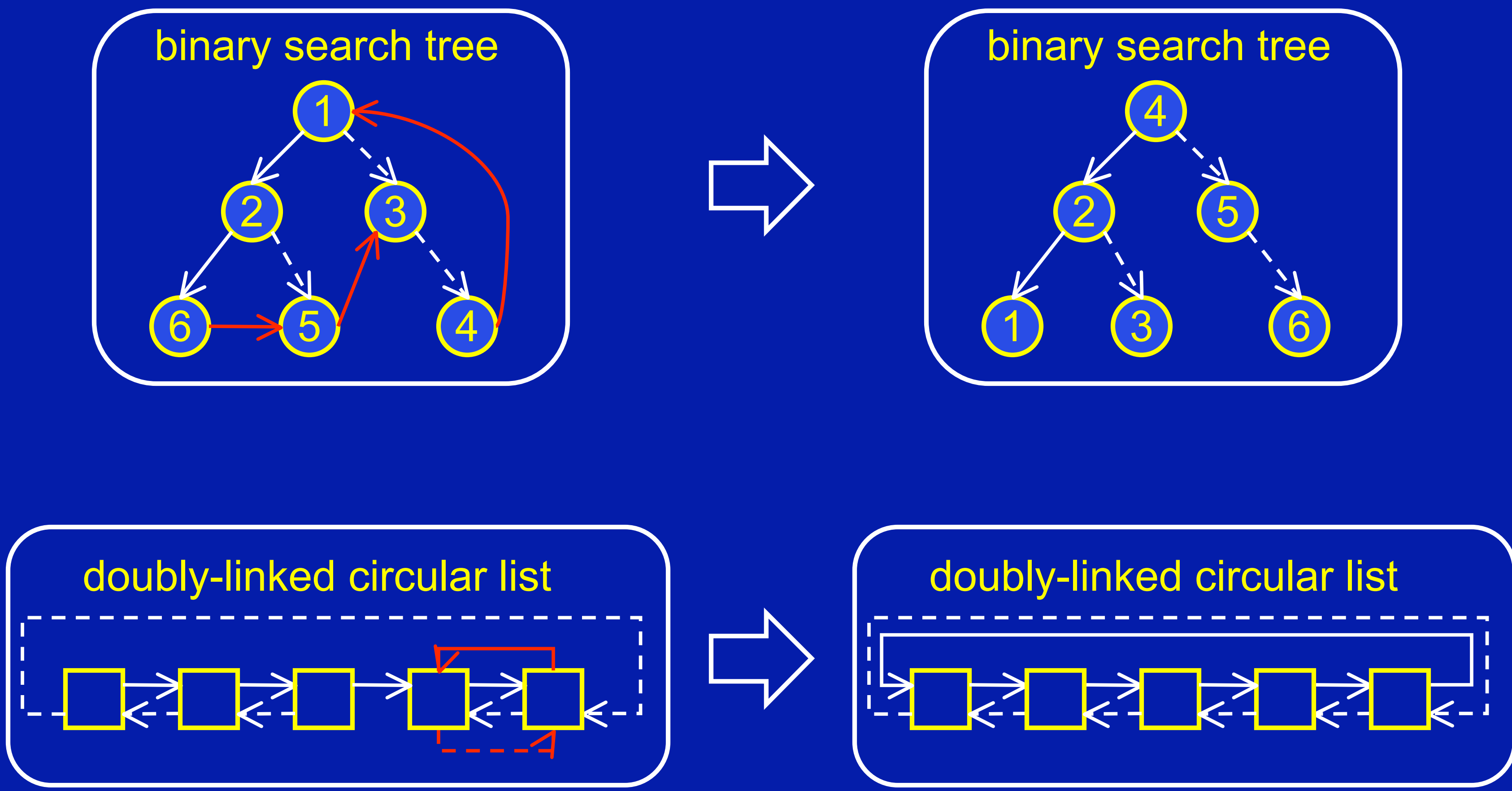
enable automated checking, e.g., via test generation

can be synthesized, even for complex structures [TACAS'07]

repair examples

corrupt

repaired



what does repair mean?

given a structure s and a repOk where !s.repOk(), generate s' such that s'.repOk() and s' is *similar* to s

- similarity is a heuristic notion
  - worst-case repair may generate a structure quite different from the original one

does **not** aim to generate a structure that a hypothetical correct program would have computed

aims to generate a structure that is within an acceptable envelope of computation

can be specified using a specification (cf. postconditions)

- e.g., the repaired structure contains all data elements reachable from the root of the corrupt structure

overview of our repair algorithm

uses the violated assertion as a **basis** of performing repair

- executes repOk and monitors its execution to isolate a component that is *necessarily* corrupt

systematically searches a neighborhood of the corrupt structure

uses a **hybrid** form of symbolic execution

- treats symbolically only a dynamic subset of all object fields---the remaining fields have concrete values

performs efficient and effective repair

outline

overview

background: symbolic execution

our approach

discussion

forward symbolic execution

technique for executing a program on symbolic input values

- pioneered three decades ago [boyer+75, king76]

explore program paths

- for each path, build a *path condition*
- check satisfiability of path condition

various applications

- test generation and program verification

traditional use focused on programs with fixed number of integer variables

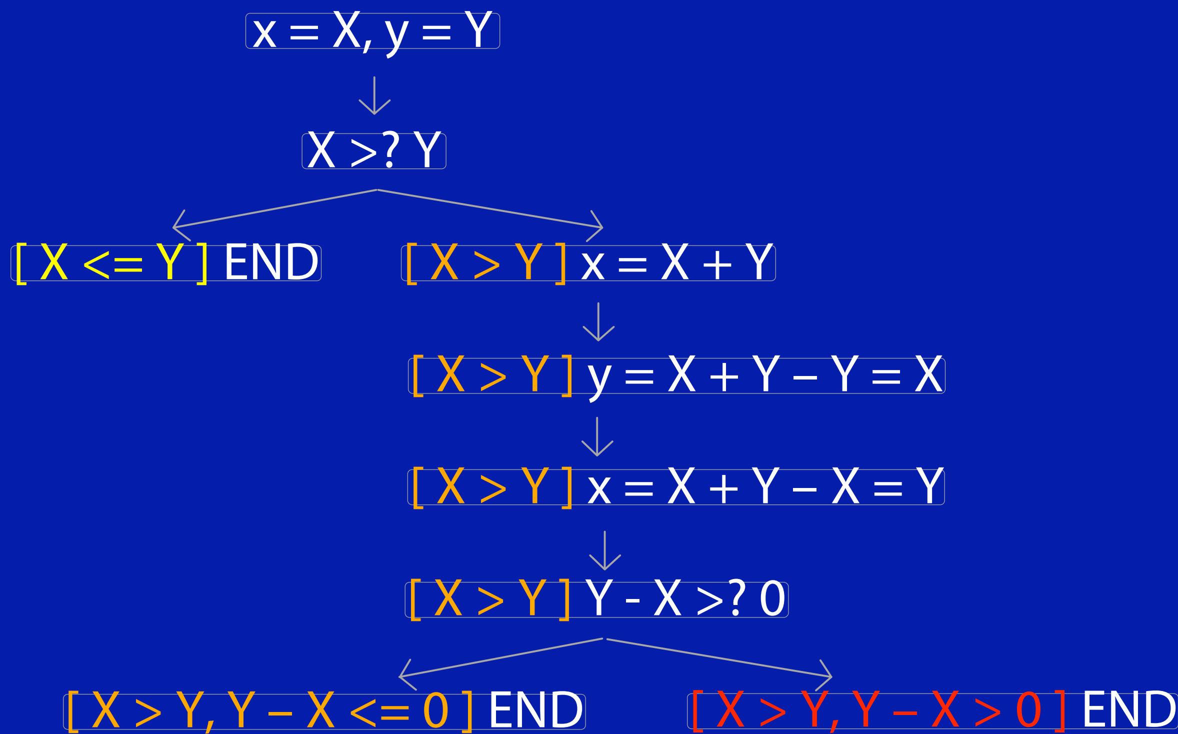
recent generalizations handle more general java/C++ code [khurshid+03, pasareanu+04, visser+04, xie+04, csallner+05, godefroid+05, cadar+05, sen+05]

concrete execution path (example)

`int x, y;`	x = 1, y = 0
`if (x > y) {`	1 >? 0
`    x = x + y;`	x = 1 + 0 = 1
`    y = x – y;`	y = 1 – 0 = 1
`    x = x – y;`	x = 1 – 1 = 0
`    if (x – y > 0)`	0 – 1 >? 0
`        assert(false);`	
`}`	

symbolic execution tree (example)

```
int x, y;

if (x > y) {

   x = x + y;

   y = x – y;

   x = x – y;

   if (x – y > 0)

      assert(false);

}
```



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algorithm: outline

to repair structure s

- execute s.repOk() and monitor the execution
  - note the order in which object fields in s are accessed
- when execution evaluates to false, backtrack and modify the value of the **last** field accessed
  - modify the value to a new (symbolic) value that is not equal to the original one
- re-execute repOk

algorithm based on korat [ISSTA'02] and generalized symbolic execution [TACAS'03]

algorithm: field value update

primitive field

- assume field f originally has value v
- assign f a symbolic value S
- add to path condition the constraint S != v

reference field

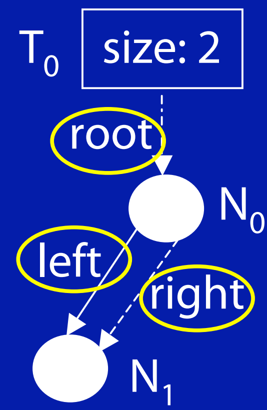
- non-deterministically assign
  - null (if original value is non-null)
  - an object of a compatible type already encountered during the current execution (if the field was not originally pointing to this object)
  - a new object (if the field was not originally pointing to an object different from those previously encountered)

illustration: binary tree

```
class BinaryTree {
   int size;
   Node root;

   static class Node {
      int info;
      Node left, right;
   }

   boolean repOk() { ... }

   void add(int e) {
      assert repOk();
      ...
   }
}
```

example execution

```
boolean repOk() {
  if (root == null) return size == 0; // empty tree

  Set visited = new HashSet();
  LinkedList workList = new LinkedList();
  visited.add(root);
  workList.add(root);
  while (!workList.isEmpty()) {
    Node current = (Node)workList.removeFirst();
    if (current.left != null) {
      if (!visited.add(current.left)) return false; // sharing
      workList.add(current.left);
    }
    if (current.right != null) {
      if (!visited.add(current.right)) return false; // sharing
      workList.add(current.right);
    }
  }
  if (visited.size() != size) return false; // inconsistent size
  return true;
}
```

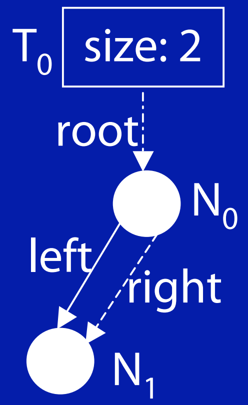


field accesses:
[T_0.root, N_0.left, N_0.right]

repair action

backtracking on [T_0.root, N_0.left, N_0.right]

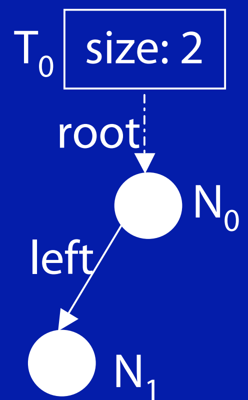
T_0 root	T_0 size	N_0 left	N_0 right	N_1 left	N_1 right
N_0	2	N_1	N_1	null	null



produces next candidate structure

T_0 root	T_0 size	N_0 left	N_0 right	N_1 left	N_1 right
N_0	2	N_1	null	null	null

- which **satisfies** repOk



implementation

written in java

has three main components

- search
    - implements systematic backtracking
- symbolic execution
    - implements library classes for hybrid symbolic execution
    - uses CVC-lite for constraint solving
- program instrumentation
    - translates java bytecode using BCEL and javassist

can handle complex structures

optimizations

efficiency

- heuristics

effectiveness

- preserve reachability of data values
- abstraction functions to compare pre/post repair structures

usefulness

- abstract repair log

performance

evaluated on a suite of text-book data structures

- singly/doubly-linked lists, binary search trees, etc.

for a small number of faults (<= 10), algorithm can repair structures with a few hundred nodes in less than 10 sec

does not scale to large data structures

- but we are working on several optimizations

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applicability: how hard is it to write assertions?

any technique for repair has a cost, e.g., the cost of writing a repair routine correctly

assertion-based repair has minimal cost

- assertions are written in the programming language
- assertion describes *what*; repair routine describes *how*
- properties are known at time of implementation but efficient repair routines may not be
  - e.g., red-black tree invariants are well-known but there are no text-book algorithms to repair them
- assertions may already be present in code
  - e.g., due to systematic testing or defensive programming

scalability: how efficient can repair be?

repair considers the problem of generating one (large) structure

korat [ISSTA'02], TestEra [ASE'01] show feasibility of exhaustive generation of a large number of small structures

results from analogous SAT problems indicate repair should be easier than exhaustive generation

- finding one solution is easier than model counting [Wei+05]
- moreover, w.h.p. we expect the repaired structure to lie in a close neighborhood of the corrupt structure
  - repair is therefore analogous to finding one solution to a SAT formula that is satisfiable w.h.p.
    - local search is expected to work well [Hoos99]

our recent work

static analysis for repair [OOPSLA 2007]

- uses cahoon and mckinley's recurrent field analysis
- prioritizes repair actions based on whether a field recurs
- enables repair of larger structures

constraint-based generation of large test inputs [ECOOP 2007]

- repairs randomly generated object graphs of a desired size
- enables efficient generation of larger test inputs

repairing programs [UT-TR 2006]

- translates repair actions in code that performs repair

related work

fault-tolerance and error recovery have featured in software systems for a long time

most of the past work has been on specialized repair routines

- file system utilities, such as fsck
- commercial systems, such as IBM MVS operating system and lucent 5ESS switch

demsky and rinard’s constraint-based framework [OOPSLA’03]

- constraints in first-order logic define desired structures
- mapping defines data translations
- repair is ad hoc
- requires users to provide mappings and learn a new constraint language

summary of assertion-based repair

a novel view of assertions

- use violated assertions as basis for repair

an algorithm for repair using symbolic execution

- a non-conventional application of backtracking search

still not practical for very large structures in deployed systems

opens a promising direction for future work

- a unified framework for verification and error recovery
  - systematic testing before deployment
  - systematic repair once deployed

khurshid@ece.utexas.edu
http://www.ece.utexas.edu/~khurshid