taking symbolic execution to the libraries

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assert-first programming

programmers have long used assertions to state crucial properties of code

- various dynamic and static analyses make use of assertions

we believe we can squeeze more value from assertions and make them a viable form of program annotations

- testing
- repair

abstract symbolic execution provides enabling technology

- can unify software verification and resilient computing

assert-first programming has the potential to provide the benefits of test-first programming but at a lower cost

- it is easier to write an assertion than to manually construct a high quality test suite or a correct repair routine

our take on symbolic execution

problem with traditional symbolic execution: it does not scale

proposed solution: try not to perform it fully symbolically

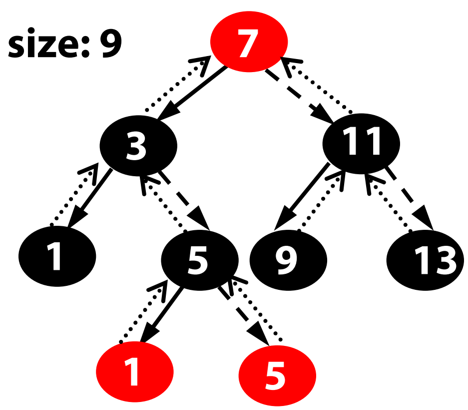
- treat a handful of fields symbolically
  - e.g., in repair, we selectively make fields symbolic
- provide direct support for symbolic execution of certain (commonly used) classes
  - give semantics for symbolic manipulations of objects and solve constraints in ensuing path conditions
  - alleviate the need to symbolically execute intricate implementations of library code
    - prevent path conditions from becoming too complex and choking underlying solvers

example

consider a red-black tree

- binary search tree
- red nodes have black children
- same number of black nodes on all paths from root to leaf

```
class TreeMap {
    Entry root;
    int size;
    static class Entry {
        int key;
        Entry left, right, parent;
        boolean color;
    }
    ...
```



assertion example

class invariant of TreeMap

```
boolean repOk {
    if (root == null) return size == 0; // empty tree
    if (root.parent != null) return false; // root has no parent
    // check acyclicity and parent relation
    Set visited = new HashSet();
    List workList = new LinkedList();
    workList.add(root);
    while (!workList.isEmpty()) {
            ...
    }
    if (visited.size() != size) return false; // check size
    ... // check colors
    ... // check keys
    return true;
}
```

test generation example

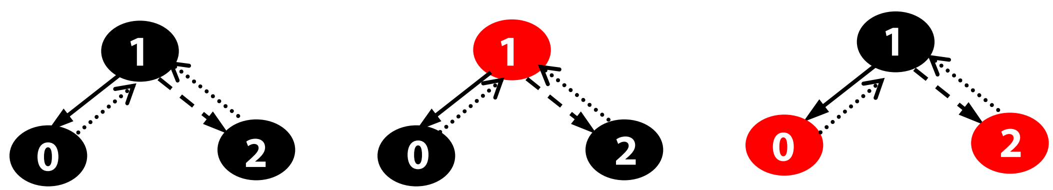
korat: monitor executions of repOk to systematically enumerate inputs for which repOk returns true [boyapati+02, marinov05]

- provides non-isomorphic generation

simple to implement using a model checker [khurshid+03]

efficient for enumerating a large number of small (~ a dozen nodes) structures

example: size=3, i.e., 3 nodes, 3 keys

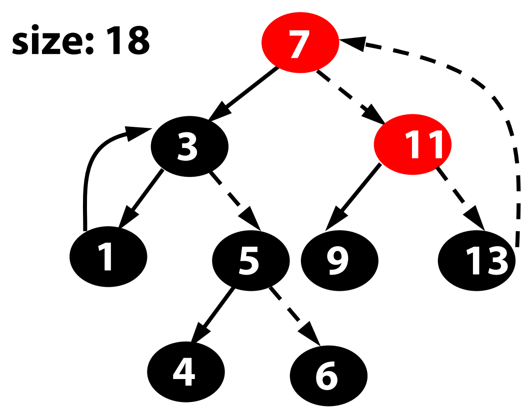


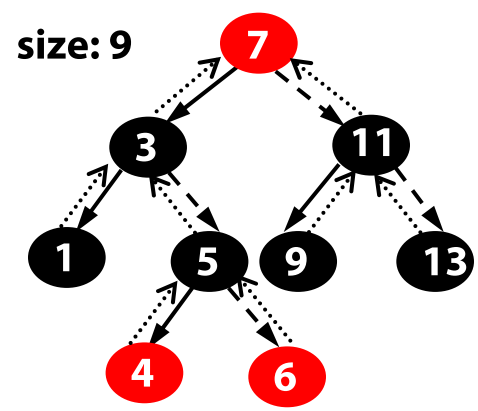
repair example

juzi: on assertion violation, *repair* the state of the program and let it continue to execute [garcia05, khurshid+05, suen05]

can be efficient for repairing large structures (~ 10K nodes) with a small number of corruptions

example





resilient computing background

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 framework is more generic [OOPSLA'03]

- declarative constraints define desired structures
- mapping defines data translations between abstract and concrete states
- requires users to provide mappings and learn a new constraint language

outline

motivation

traditional symbolic execution

- supporting references

supporting library classes

- towards an implementation

discussion

traditional 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

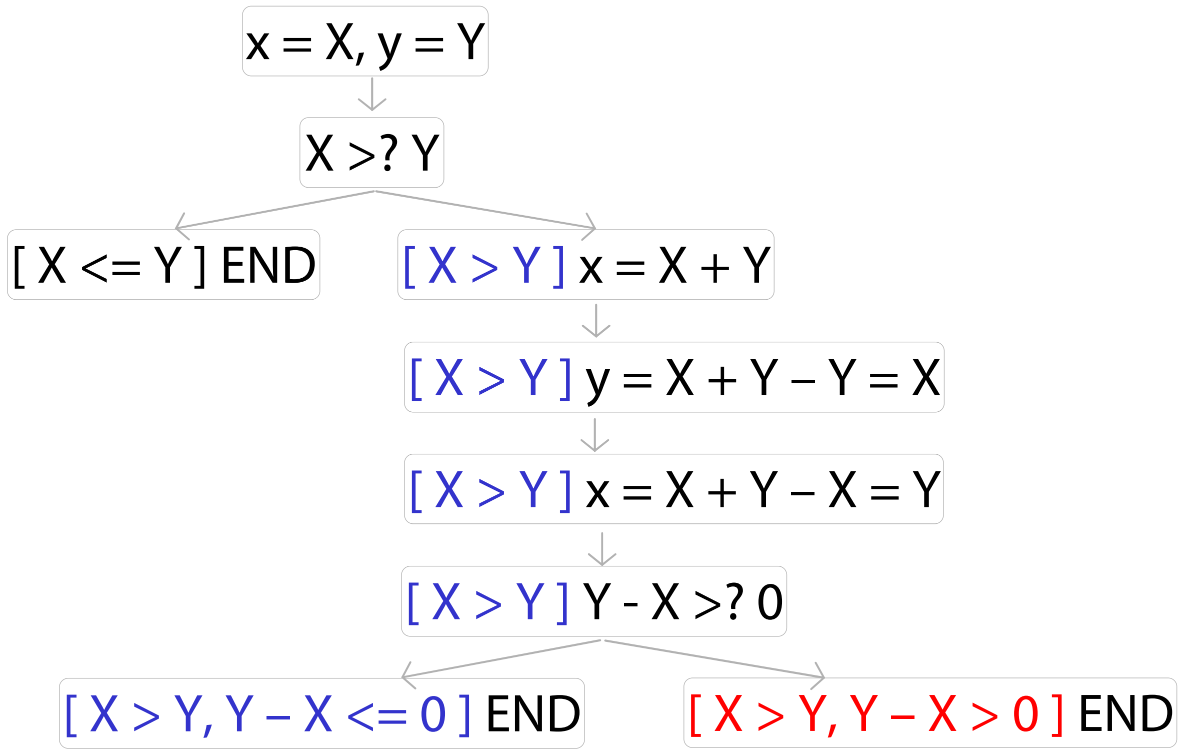
traditional use focused on programs with fixed number of variables of primitive types

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);

}
```



handling more general programs

how to handle programs with references or pointers?
  e.g., if (current.left.parent != current) ...

several recent approaches work with arbitrary java/C++ programs
  [khurshid+03, pasareanu+04, visser+04, xie+04, csallner+05, godefroid+05, cadar+05]

common theme: perform symbolic execution at **concrete representation level**

example algorithm

to symbolically execute a method m

- create input objects with uninitialized fields
- execute m
  - follow mainly Java semantics
  - systematically initialize fields on **first-access**
  - add constraints to path condition and check for feasibility

example field initialization

idea: on first access of a field, non-deterministically initialize it to explore all aliasing possibilities

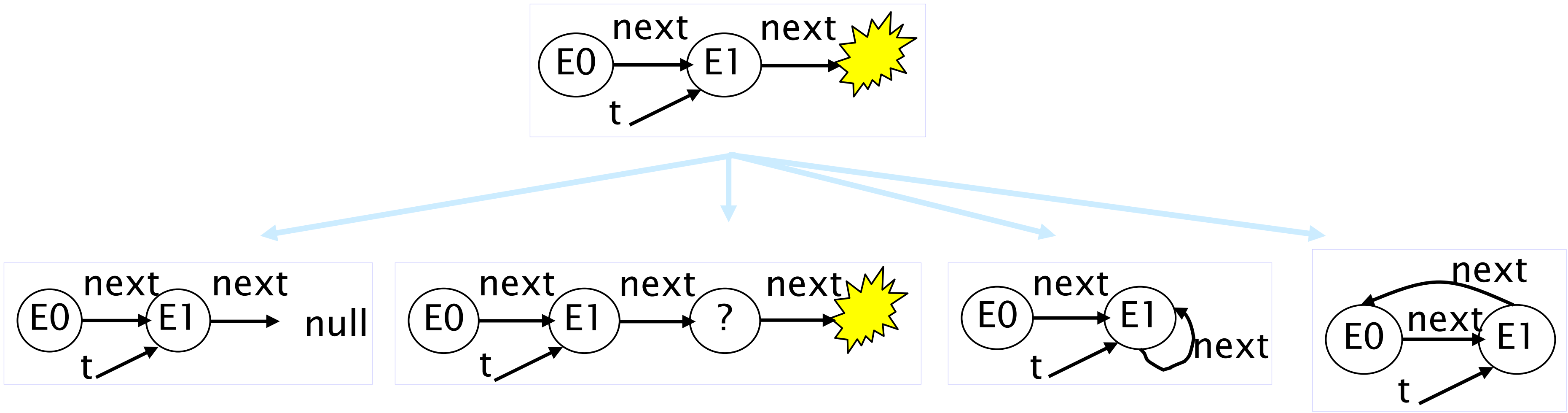
when method execution accesses field f

```
if (f is uninitialized) {
    if (f is reference field of type T) {
        non-deterministically initialize f to
        – null
        – a new object of class T (with uninitialized fields)
        – an object created during prior field initialization
    }
    if (f is numeric field)
        initialize f to a new symbolic value
}
```

algorithm illustration

consider executing the statement

    next = t.next;



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abstract symbolic execution (dianju)

basically the same algorithm as before **except** that objects and methods of supported classes are treated specially

- building constraints on symbolic objects based on predicates
- updating state of symbolic objects based on state modifiers

path conditions may represent rich constraints, e.g., string_0.equals("hello") and !set_0.contains(int_0)

dedicated constraint solvers, e.g., for strings, sets, and maps

- based on dedicated generators, e.g., for generating mathematical objects that represent sets (or maps)
    - can be focused to avoid/provide generation of certain values, e.g., a set must contain the value null

TestEra [ASE'01] had direct support for objects encapsulating primitives and arrays; GSE [TACAS'03] handled strings

example benefits in test generation

consider generating objects of class Test where field s is initialized to HashSet objects

```
class Test {
    Set<Integer> s; // s != null
}
```

dianju does not require detailed class invariant

- e.g., s != null suffices; no need for invariant for HashSet

as an (extreme) example consider generating tests with 9 integers

- korat evaluates 3M candidates and generates 26K valid structures, while dianju evaluates $2^9 = 512$ candidates
- for systematic testing of library implementations, korat's approach is necessary; for client code, dianju's suffices

implementation via instrumentation

implementation has three basic components

- special libraries that implement basics of symbolic execution
  - support for manipulation of symbolic objects
  - constraint solvers, including use of off-the-shelf DP implementations, e.g., CVC-lite [barrett+04]
- a bytecode instrumentation engine that allows using a standard JVM to perform symbolic execution
  - introduces new fields and methods; replaces declarations and operations on supported types with special libraries
  - uses BCEL [dahm, bcel.sourceforge.net], javassist[chiba98]
- a systematic backtracking mechanism

can be implemented using off-the-shelf model checkers

instrumentation example

add shadow fields to keep track of field accesses

```
Entry left; boolean left_is_symbolic;
```

replace field accesses with invocations of new methods

```
this.left → this.left()
where
Entry left() {
    if (left_is_symbolic) {
        left_is_symbolic = false;
        left = ...; // non-deterministic initialization
    }
    return left;
}
```

implemented using bytecode manipulation

```
6:  getfield         #18;//Field left:Ldianju/examples/TreeMap$Entry;
6:  invokevirtual #252;//Method left:()Ldianju/examples/TreeMap$Entry;
```

nondeterministic initialization

the class Explorer allows emulating nondeterministic choice

- choose method returns an integer value nondeterministically

```
Explorer.initialize();
do {
  ...
  // i is systematically initialized to 0, 1, 2
  int i = Explorer.choose(2);
  ...
} while (Explorer.incrementCounter());
```

simple stateless search, similar to VeriSoft [Godefroid97]

- bounded depth-first

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how symbolic execution enables testing

black-box [ISSTA 2002]

- symbolically execute `repOk`; inputs for which it returns true are desired test inputs

white-box/hybrid [TACAS 2003, ISSTA 2004]

- symbolically execute method under test; on field initialization, take into account preconditions

how symbolic execution enables repair

to repair structure s [SPIN 2005]

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

role of assertions

efficient symbolic execution can unify software verification and resilient computing via the use of assertions

- systems can be systematically tested before deployment as well as ensured to behave as expected once deployed

applicability

- assertion-based techniques have minimal cost
  - assertion describes *what*; test generator or repair routine describes *how*

scalability

- it is possible to abstract away from irrelevant details

assertions are already immensely popular in hardware verification; the time has also come that we realize the potential benefits assertions have long offered in software

?/!

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