Advanced Software Testing and Debugging (CS598)

Spec-based Testing

Spring 2022

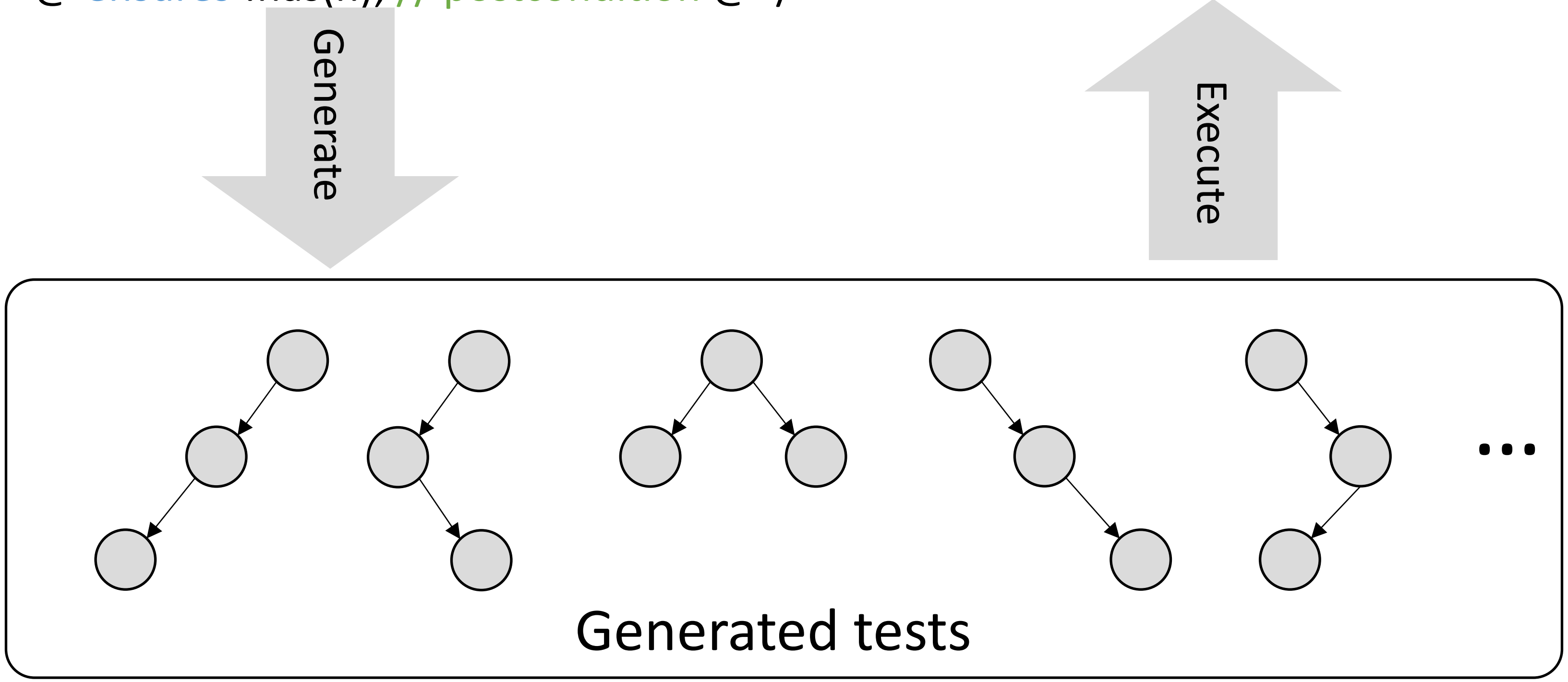
Lingming Zhang

Reminder

- Check your presentation schedule on course website
- Form your course project team (you can work individually!)
  - Post on Campuswire (#find-teammates) if you need to find a teammte
  - Or let me know if you need help
- Proposal presentation (Feb 17, in class)
- Proposal submission (Feb 21, 11:59pm)
  - Join your group on Campuswire before submission as this is a group assignment
    - If you are working by yourself, join any empty group on Campuswire ("People"->"Groups")
    - If you have a teammate, make sure you join the same group as your teammate

Spec-based test generation

```
// specification for removing from binary tree
/*@ public normal_behavior
   @ requires has(n); // precondition
   @ ensures !has(n); // postcondition @*/
```



This class

- Korat: Automated Testing Based on Java Predicates (ISSTA'02)
- TestEra: A Novel Framework for Automated Testing of Java Programs (ASE'01)

What specifications to use?

- Formal specifications in specifically designed languages (e.g., Z and Alloy)
  - Precise and concise
  - Hard to write (steep learning curve)

- Korat directly utilizes **Java predicates** for encoding the specifications
  - Some existing formal specifications (e.g., JML) can be automatically transformed to Java
  - **Programmers can also use the full expressiveness of the Java language to write specifications!**

Korat predicate

```
class BinaryTree {
  private Node root; // root node
  static class Node {
    private Node left; // left child
    private Node right; // right child
  }
  …
}
```

BinaryTree Program

```
public boolean repOk() {
  if (root == null) return true; // empty tree
  Set visited = new HashSet();
  visited.add(root);
  LinkedList workList = new LinkedList();
  workList.add(root);
  while (!workList.isEmpty()) {
    Node current = (Node)workList.removeFirst();
    if (current.left != null) {
      if (!visited.add(current.left)) return false; // tree has no cycle
      workList.add(current.left);
    }
    if (current.right != null) {
      if (!visited.add(current.right)) return false; // tree has no cycle
      workList.add(current.right);
    }
  }
  return true; // valid non-empty tree
}
```

Korat RepOK predicate

Finitization

- **Finitization**: a set of bounds that limits the size of the inputs
  - Specifies the number of objects for each used class
    - A set of objects of one class forms a **class domain**
  - Specifies the set of classes whose objects each field can point to
    - The set of values a field can take forms its **field domain**
    - Note that a field domain is a union of some class domains

```
public static Finitization finBinaryTree(int NUM_Node) {
  Finitization f = new Finitization(BinaryTree.class);
  ObjSet nodes = f.createObjects("Node", NUM_Node);
  nodes.add(null);
  f.set("root", nodes);
  f.set("Node.left", nodes);
  f.set("Node.right", nodes);
  return f;
}
```

Generated finitization description for BinaryTree

State space

- **finBinaryTree** with **NUM_Node=3**

BinaryTree	**N0**		**N1**		**N2**	
root	left	right	left	right	left	right
?	**?**	**?**	**?**	**?**	**?**	**?**

- Each field with type Node includes 4 possible choices:
  - {null, N0, N1, N2}
- Total number of possible tests for a tree with 3 nodes:
  - $4*(4*4)^3=2^{14}$=16,384
- Total number of possible tests for a tree with **n** nodes:
  - $(n+1)*((n+1)*(n+1))^n=(n+1)^{2n+1}$

State space: more examples

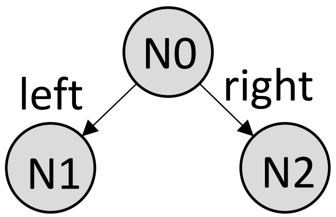
- The number of “trees” explodes rapidly!
  - n=3: over 16,000 “tests”
  - n=4: over 1,900,000 “tests”
  - n=5: over 360,000,000 “trees”
- Limit us to only very small input sizes

Are they all valid tests?

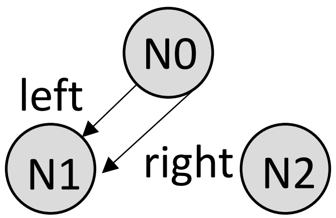
State space: examples

- **finBinaryTree** with **NUM_Node=3**

BinaryTree	**N0**		**N1**		**N2**	
root	left	right	left	right	left	right
N0	**N1**	**N2**	**null**	**null**	**null**	**null**



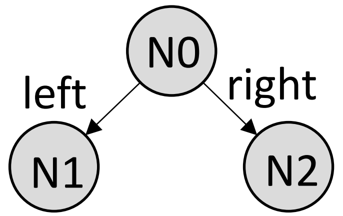
BinaryTree	**N0**		**N1**		**N2**	
root	left	right	left	right	left	right
N0	**N1**	**N1**	**null**	**null**	**null**	**null**



State space: vector representation

- To systematically explore the state space, Korat orders all the elements in every class domain and every field domain
  - The ordering in each field domain is consistent with the orderings in the class domains
- Each candidate input is then a vector of field domain indices!

BinaryTree	N0		N1		N2	
root	left	right	left	right	left	right
N0	**N1**	**N2**	**null**	**null**	**null**	**null**



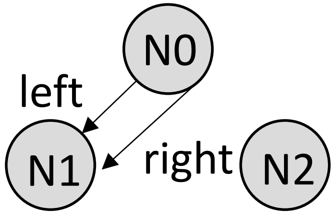
Test: [1, 2, 3, 0, 0, 0, 0]

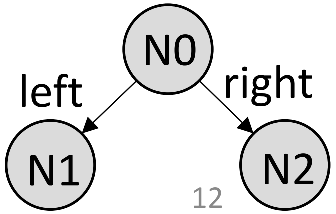
Class domain: [N0, N1, N2]
Field domain: [null, N0, N1, N2]

Search

- The search starts with the candidate vector set to all zeros
- Then, iterate through the following steps:
  - Construct the actual test based on the current vector
  - Invoke **repOK()** to check the test validity and record accessed field ordering
  - Increment the field domain index for the last field in the **recorded field ordering**
    - If the index exceeds the limit, reset it to 0 and increment the previous field in field ordering

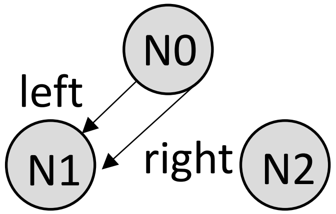
	BinaryTree	**N0**		**N1**		**N2**	
	root	left	right	left	right	left	right
	N0	**N1**	**N1**	**null**	**null**	**null**	**null**
Current:	[1,	2,	2,	?,	?,	?,	?]
Next:	[1,	2,	**3**,	?,	?,	?,	?]

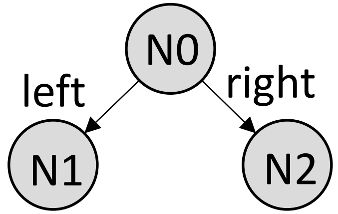




Search: why field ordering accessed matters

	BinaryTree	**N0**		**N1**		**N2**	
	root	left	right	left	right	left	right
	N0	**N1**	**N1**	**null**	**null**	**null**	**null**
Current:	[1,	2,	2,	?,	?,	?,	?]
Next:	[1,	2,	**3**,	?,	?,	?,	?]





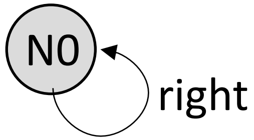
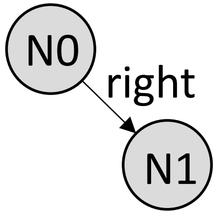
- Any test vectors of the form [1,2,2,?,?,?,?] are invalid!
- Keeping the accessed field ordering enables us to prune all such tests
  - 4^4 tests pruned for this single step!

Search: why field ordering accessed matters (cont.)

	BinaryTree	N0		N1		N2		
	root	left	right	left	right	left	right	
	null	null	null	null	null	null	null	
Current:	[0,	?,	?,	?,	?,	?,	?]	**null**
Next:	[**1**,	?,	?,	?,	?,	?,	?]	N0

- Only the root is accessed since it is **null**
- Any test vectors of the form [0,?,?,?,?,?,?] do not need to be repeated!
- Keeping the accessed field ordering enables us to prune all such tests
  - 25% of all tests pruned by this single test input!

Search: example

BinaryTree root	N0 left	N0 right	N1 left	N1 right	N2 left	N2 right	
null	**null**	**null**	**null**	**null**	**null**	**null**	**null**
1							
N0	**null**	**null**	**null**	**null**	**null**	**null**	
1	2	3					
N0	**null**	**N0**	**null**	**null**	**null**	**null**	
1	2	3					
N0	**null**	**N1**	**null**	**null**	**null**	**null**	
1	2	3	4	5			

… **Can we further prune the state space?**

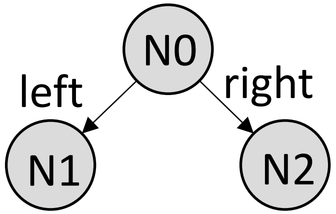
Isomorphism

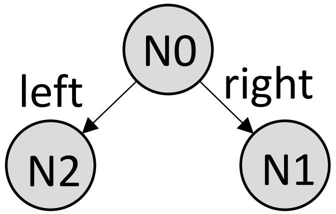
- **O**: $\mathbf{O_1} \cup \ldots \cup \mathbf{O_n}$, the sets of objects from **n** classes
- **P**: the set consisting of **null** and all values of primitive types that objects in **O** can reach
- Two candidates, **C** and **C'**, are *isomorphic* iff there is a permutation **π** on **O**, mapping objects from $\mathbf{O_i}$ to objects from $\mathbf{O_i}$ for all $\mathbf{1 \le i \le n}$, such that: $\forall \mathbf{o, o' \in O.}\ \forall \mathbf{f \in fields(o).}\ \forall \mathbf{p \in P.}$
  - **o.f==o' in C iff π(o).f==π(o') in C' AND**
  - **o.f==p in C iff π(o).f==p in C'**

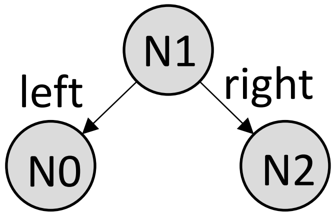
Two data structures are isomorphic if a permutation exists between the two that preserves structure

Isomorphism: examples

	BinaryTree	N0		N1		N2	
	root	left	right	left	right	left	right
	N0	N1	N2	null	null	null	null
Test1:	[1,	2,	3,	0,	0,	0,	0]
	N0	N2	N1	null	null	null	null
Test2:	[1,	3,	2,	0,	0,	0,	0]
	N1	null	null	N0	N2	null	null
Test3:	[2,	0,	0,	1,	3,	0,	0]







They are isomorphic!

We just need one of them…

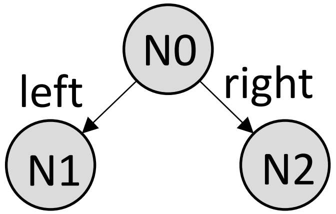
Nonisomorphism

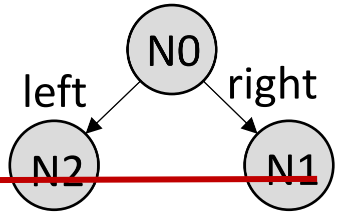
- **Algorithm**: only allow an index into a given class domain to exceed previous indices into that domain by 1
  - Initial prior index: -1
- **Example**: assume we are generating tests with three fields from the same class domain

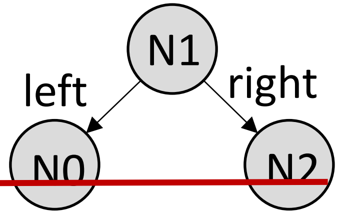
0 0 0	~~1~~ 0 0	~~2~~ 0 0
0 0 1	~~1~~ 0 1	~~2~~ 0 1
0 0 ~~2~~	~~1~~ 0 2	~~2~~ 0 2
0 1 0	~~1~~ 1 0	~~2~~ 1 0
0 1 1	~~1~~ 1 1	~~2~~ 1 1
0 1 2	~~1~~ 1 2	~~2~~ 1 2
0 ~~2~~ 0	~~1~~ 2 0	~~2~~ 2 0
0 ~~2~~ 1	~~1~~ 2 1	~~2~~ 2 1
0 ~~2~~ 2	~~1~~ 2 2	~~2~~ 2 2

Nonisomorphism: more examples

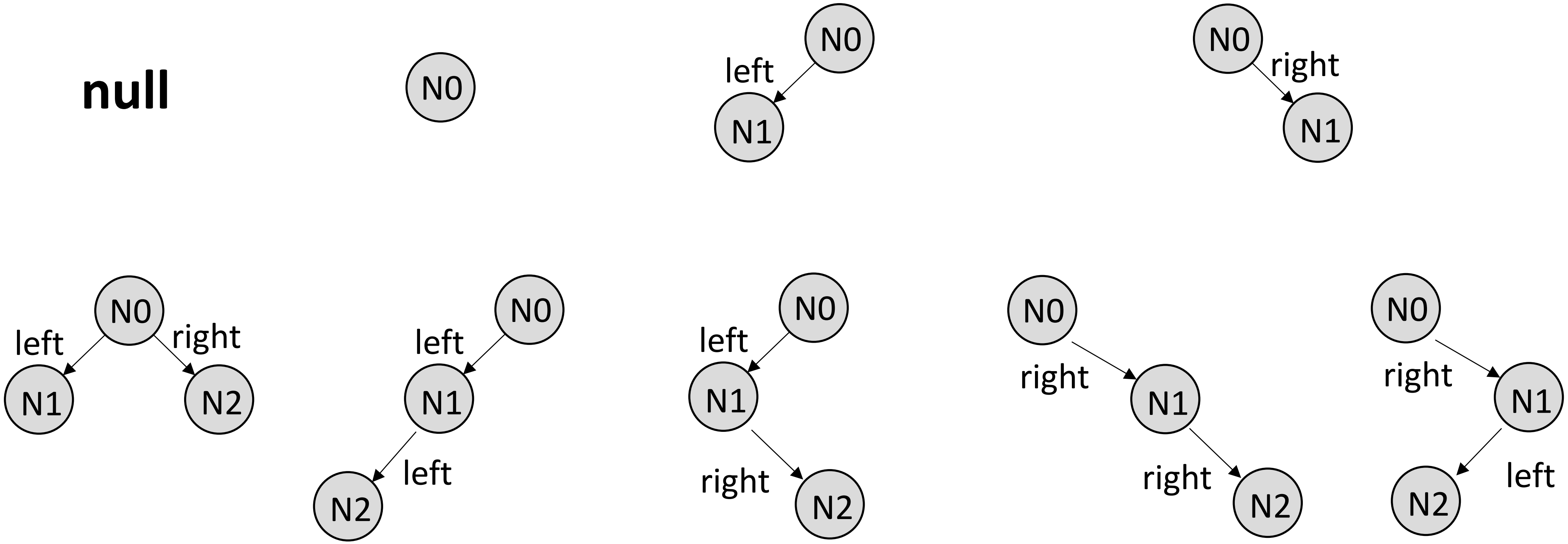
	BinaryTree	N0		N1		N2	
	root	left	right	left	right	left	right
	N0	**N1**	**N2**	**null**	**null**	**null**	**null**
Test1:	[1,	2,	3,	0,	0,	0,	0]
	N0	**N2**	**N1**	**null**	**null**	**null**	**null**
~~**Test2**:~~	~~[1,~~	~~3,~~	~~2,~~	~~0,~~	~~0,~~	~~0,~~	~~0]~~
	N1	**null**	**null**	**N0**	**N2**	**null**	**null**
~~**Test3**:~~	~~[2,~~	~~0,~~	~~0,~~	~~1,~~	~~3,~~	~~0,~~	~~0]~~







Korat results for BinaryTree with up to 3 nodes



- Only 9 valid tests out of 2^{14} possibilities!

Test generation

- Valid test cases for a method must satisfy its precondition
- Korat uses a class that represents method’s inputs:
  - One field for each parameter of the method (including the implicit *this*)
  - A **repOk** predicate that uses the precondition to check the validity of method’s inputs
- Given a finitization, Korat then generates all inputs with **repOk=true**

```
class BinaryTree_remove {
  BinaryTree This; // the implicit "this"
  BinaryTree.Node n; // the Node parameter
  //@ invariant repOk();
  public boolean repOk() {
    return This.has(n);
  }
}
```

```
public static Finitization
  finBinaryTree_remove(int NUM_Node) {
  Finitization f = new Finitization(BinaryTree_remove.class);
  Finitization g = BinaryTree.finBinaryTree(NUM_Node);
  f.includeFinitization(g);
  f.set("This", g.getObjects(BinaryTree.class));
  f.set("n", /***/);
  return f;
}
```

Test generation for *remove(Node n)*

Test oracle

- To check partial correctness of a method, a simple test oracle could just invoke **repOk** in the post-state to check the class invariant
- The current Korat implementation uses the JML tool-set to automatically generate test oracles from method postconditions

```
//@ public invariant repOk();  //class invariant
/*@ public normal_behavior
   @ requires has(n); // precondition
   @ ensures !has(n); // postcondition @*/
public void remove(Node n) {
 ...
}
```

JML specification for removing from binary tree

Testing activity	JUnit	JML+JUnit	Korat
Generating tests			X
Generating oracle		X	X
Running tests	X	X	X

Benchmark subjects

benchmark	package	finitization parameters
BinaryTree	korat.examples	NUM_Node
HeapArray	korat.examples	MAX_size, MAX_length, MAX_elem
LinkedList	java.util	MIN_size, MAX_size, NUM_Entry, NUM_Object
TreeMap	java.util	MIN_size, NUM_Entry, MAX_key, MAX_value
HashSet	java.util	MAX_capacity, MAX_count, MAX_hash, loadFactor
AVTree	ins.namespace	NUM_AVPair, MAX_child, NUM_String

Overall results

benchmark	size	time (sec)	structures generated	candidates considered	state space
`BinaryTree`	8	1.53	1430	54418	2^{53}
	9	3.97	4862	210444	2^{63}
	10	14.41	16796	815100	2^{72}
	11	56.21	58786	3162018	2^{82}
	12	233.59	208012	12284830	2^{92}
`HeapArray`	6	1.21	13139	64533	2^{20}
	7	5.21	117562	519968	2^{25}
	8	42.61	1005075	5231385	2^{29}
`LinkedList`	8	1.32	4140	5455	2^{91}
	9	3.58	21147	26635	2^{105}
	10	16.73	115975	142646	2^{120}
	11	101.75	678570	821255	2^{135}
	12	690.00	4213597	5034894	2^{150}
`TreeMap`	7	8.81	35	256763	2^{92}
	8	90.93	64	2479398	2^{111}
	9	2148.50	122	50209400	2^{130}
`HashSet`	7	3.71	2386	193200	2^{119}
	8	16.68	9355	908568	2^{142}
	9	56.71	26687	3004597	2^{166}
	10	208.86	79451	10029045	2^{190}
	11	926.71	277387	39075006	2^{215}
`AVTree`	5	62.05	598358	1330628	2^{50}

Korat vs. TestEra

benchmark	size	Korat struc. gen.	Korat total time	Korat first struc.	Alloy Analyzer inst. gen.	Alloy Analyzer total time	Alloy Analyzer first inst.
`BinaryTree`	3	5	0.56	0.62	6	2.63	2.63
	4	14	0.58	0.62	28	3.91	2.78
	5	42	0.69	0.67	127	24.42	4.21
	6	132	0.79	0.66	643	269.99	6.78
	7	429	0.97	0.62	3469	3322.13	12.86
`HeapArray`	3	66	0.53	0.58	78	11.99	6.20
	4	320	0.57	0.59	889	171.03	16.13
	5	1919	0.73	0.63	1919	473.51	39.58
`LinkedList`	3	5	0.58	0.60	10	2.61	2.39
	4	15	0.55	0.65	46	3.47	2.77
	5	52	0.57	0.65	324	14.09	3.51
	6	203	0.73	0.61	2777	148.73	5.74
	7	877	0.87	0.61	27719	2176.44	10.51
`TreeMap`	4	8	0.75	0.69	16	12.10	6.35
	5	14	0.87	0.88	42	98.09	18.08
	6	20	1.49	0.98	152	1351.50	50.87
`AVTree`	2	2	0.55	0.65	2	2.35	2.43
	3	84	0.65	0.61	132	4.25	2.76
	4	5923	1.41	0.61	20701	504.12	3.06

Korat for methods

benchmark	method	max. size	test cases generated	gen. time	test time
BinaryTree	remove	3	15	0.64	0.73
HeapArray	extractMax	6	13139	0.87	1.39
LinkedList	reverse	2	8	0.67	0.76
TreeMap	put	8	19912	136.19	2.70
HashSet	add	7	13106	3.90	1.72
AVTree	lookup	4	27734	4.33	14.63

Discussion

- Strengths
- Limitations
- Future work

This class

- Korat: Automated Testing Based on Java Predicates (ISSTA'02)
- TestEra: A Novel Framework for Automated Testing of Java Programs (ASE'01)

TestEra vs Korat

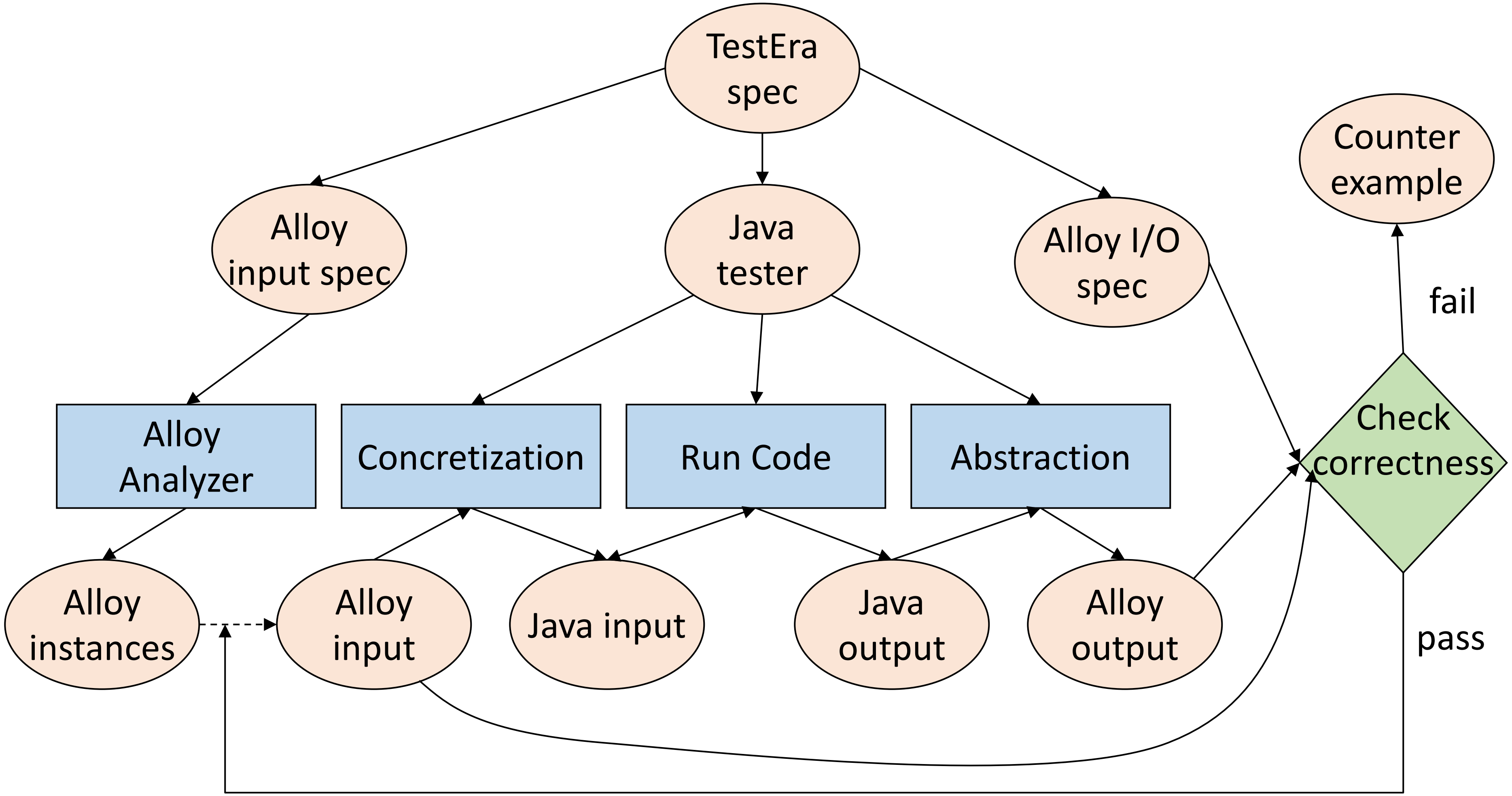
- Similarities:
  - Both target structurally complex test input generation based on specifications
  - Both automatically generate all non-isomorphic tests within a given input size
- Differences
  - TestEra uses Alloy[1] as the specification language
    - Alloy is a simple declarative language based on first-order logic
  - TestEra uses Alloy and Alloy Analyzer to generate the tests and to evaluate the correctness criteria
  - TestEra produces concrete Java inputs as counterexamples to violated correctness criteria

[1] https://www.csail.mit.edu/research/alloy

TestEra components

- A specification of inputs to a Java program written in Alloy
  - Class invariant and precondition
- A correctness criterion written in Alloy
  - Class invariant and post-condition
- An concretization function
  - Which maps instances of Alloy specifications to concrete Java objects
- An abstraction function
  - Which maps the concrete Java objects to instances of Alloy specifications

TestEra big picture



TestEra: example

```
class List {
  int elem;
  List next;
  static List mergeSort(List l) { ... }
}
```

Java code

```
module list
import integer
sig List {
  elem: Integer,
  next: lone List
}
```

Alloy model

- A recursive method for performing merge sort on acyclic singly linked lists

- Signature declaration introduces the List type with functions:
  - **elem: List ⟶ Integer**
  - **next: List ⟶ List**

Input specification

```
module list
import integer

sig List {
  elem: Integer,
  next: lone List }

fun Acyclic(l: List) {
  all n: l.*next | lone n.~next   // at most one parent
  no l.~next }                     // head has no parent

one sig Input in List {}

fact GenerateInputs {
  Acyclic(Input) }
```

- **~:** transpose (converse relation)
- ***:** reflexive transitive closure
- Subsignature **Input** is a subset of **List** and it has exactly one atom which is indicated by the keyword **one**

Correctness specification

```
fun Sorted(l: List) {
  all n: l.*next | some n.next => n.elem <= n.next.elem }   //?

fun Perm(l1: List, l2:List)
  all e: Integer | #(e.~elem & l1.*next) =
                 #(e.~elem & l2.*next) }   //?

fun MergeSortOK(i:List, o:List) {
  Acyclic(o)
  Sorted(o)
  Perm(i,o) }

one sig Output in List {}

fact OutputOK {
  MergeSortOk(Input, Output) }
```

- **#**: cardinality of sets

Counter-examples

- If an error is inserted in the method for merging where **(l1.elem <= l2.elem)** is changed to **(l1.elem >= l2.elem)**
- Then TestEra generates a counter example:

```
Counterexample found:
  Input List: 1 -> 1 -> 3 -> 2
  Output List: 3 -> 2 -> 1 -> 1
```

TestEra: case studies

- Red-Black trees
  - Tested the implementation of Red-Black trees in java.util.TreeMap
  - Introduced some bugs and showed that they can catch them with TestEra framework
- Intentional Naming System
  - A naming architecture for resource discovery and service location in dynamic networks
  - Found some bugs
- Alloy Analyzer
  - Found some bugs in the Alloy Analyzer using TestEra framework

Discussion

- Strengths
- Limitations
- Future work

Thanks and stay safe!