Automatic Test Generation

First, about Purify

- Paper about Purify (and PurifyPlus) posted
- How do you monitor reads and writes:
  - insert statements before and after reads, writes in code
    - can still be done with binaries
- But this affects performance
  - Without watching reads/writes, the overhead is small
  - With reads/writes, can be 10X slowdown
  - This is still OK for such a debugging tool

Homework 1

- Due Monday (Sep 23, 9 AM)
- Make sure you've started already
- If you're using Java 7 (e.g., on EDLab):

```
javac -g -source 6 -target 6 *.java
```

Questions?

Automated Test Generation Idea:

- Automatically generate tests for software

- Why?
  - Find bugs more quickly
  - Conserve resources
  - No need to write tests
  - If software changes, no need to maintain tests
  - No need for testers?

The Problem

- Automated testing is hard to do

- Probably impossible for whole systems

- Certainly impossible without specifications

Pre- & Post-Conditions

- A pre-condition is a predicate
  - assumed to hold before a function executes
- A post-condition is a predicate
  - known to hold after a function executes
  - whenever the pre-condition also holds

Example

Pre-condition: l.contains(x)

```
List remove(LinkedList l, Element x) {
  if (x == l.head())
    return l.tail();
  else
    return
      new LinkedList(l.head(),remove(l.tail(), x));
}
```

Post-condition: !(l.contains(x)

Does this post-condition hold?

How can the pre-condition change for the post condition to hold?

Are pre- and post-conditions a good idea?

- Most useful if they are executable
  - written in the programming language itself
  - a special case of assertions

- Recommended by software engineers
  - and everyone who studies software engineering

- Can reduce ambiguity in specification

- May be somewhat imprecise and incomplete
  - full pre- and post-conditions may be more complex than the code!
  - still useful even if they do not cover every situation

Using Pre- and Post-Conditions

- Pre-/Post-Conditions are specifications

- To perform a test:
  - Generate an input (any input)
  - Check that the test input satisfies the pre-condition
  - Run test
  - Check that the test result satisfies the post-condition

Helps run tests, might even help write them!

How can we generate tests?

- Randomized testing

- Mutation Testing

- Korat

Random Testing

- Feed random inputs to a program
- Observe whether it behaves “correctly”
  - execution satisfies pre- and post-conditions
  - or just doesn’t crash

    (A simple pre/post condition)

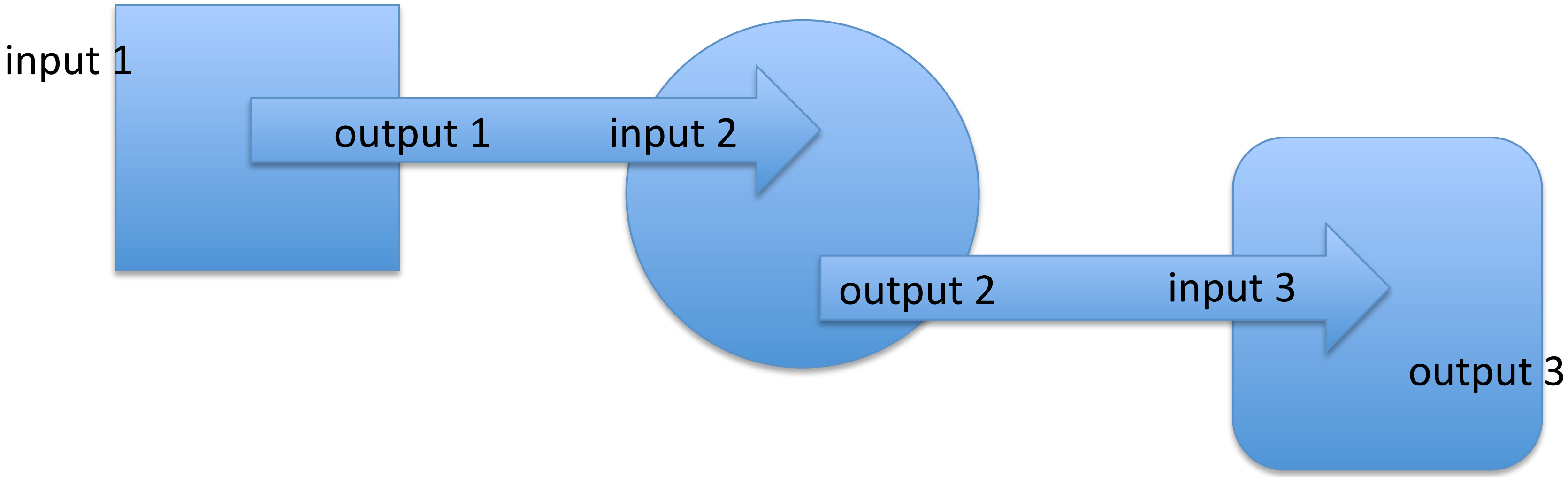
Random Testing: Good and Bad News

- Randomization is highly effective
  - easy to implement
  - provably good coverage for enough tests

- But
  - to say anything rigorous, we must be able to characterize the distribution of inputs
  - easy for string utilities
  - harder for systems with more arcane input

    for example, parsers for context-free grammars

What about staged components?



If we only control the input to the whole system (input 1), can we test the circle well?

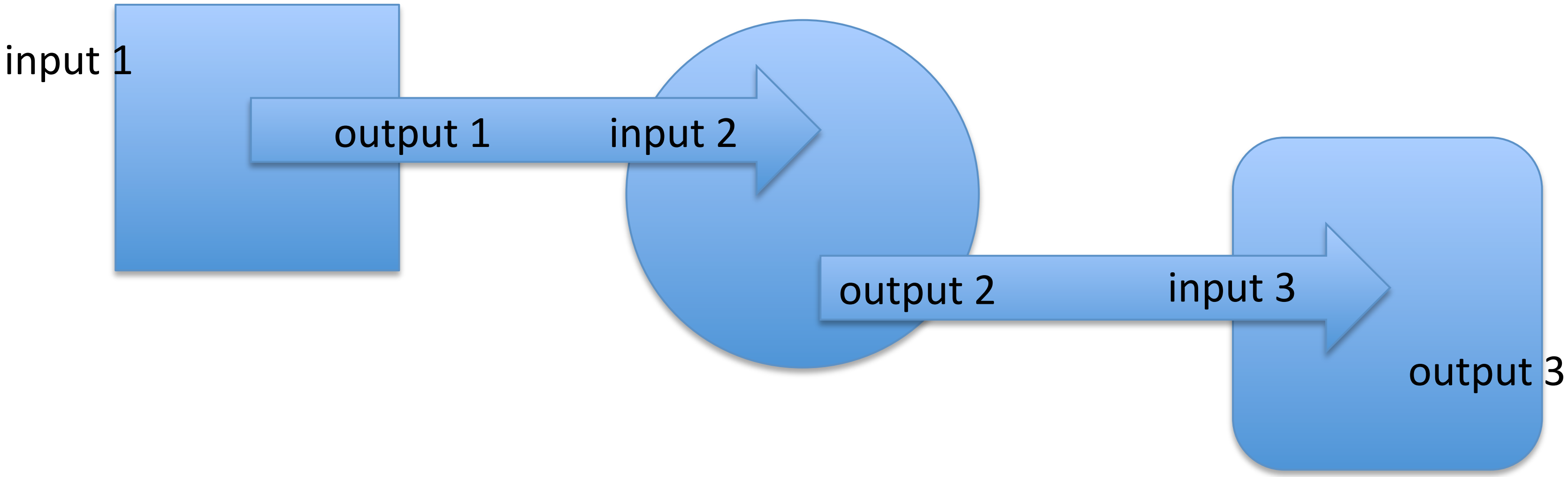
Mutation Analysis

- How do we know our test suite is any good?

- Idea: Test variations on the program
  - for example, replace `x > 0` with `x < 0`
  - or replace `i` by `i+1` or `i-1`

- If the test suite is good, it should report failed tests in the variants

Mutation testing is one way to check automated testing



input 1

output 1

input 2

output 2

input 3

output 3

Mutation Analysis Summary

- Mutate each statement in the program in finitely many different ways
- Each modification is one mutant
- Check if a set of mutants is adequate
- Find a set of test cases that distinguishes the program from the mutants

What Justifies Mutation Testing?

- Competent programmer assumption
  - the program is close to correct
- Mutations are representative of common errors
  - off by one errors, wrong comparison errors
- It formalizes test writing
  - we write tests for corner cases and off-by-one errors.
    There are an infinite number of them.
    This way, we formalize the process.
- This is a start
  - testing does not stop here

Back to automated testing

- Generate mutants of program P

- Generate tests
  (somehow)

- For each test t
  for each mutant M
    if $M(t) \neq P(t)$ mark M as killed

- If the tests kill all mutants, the tests are adequate

Generating tests

This is the hard part!

- Use weakest-preconditions
  - work backwards from statement to inputs
- Take short paths through loops
  - try it 0 times, 1 time, 2 times
- Generate symbolic constraints on inputs that must be satisfied
- Solve for inputs

What if a mutant is equivalent to the original?

- No test will kill it
- In practice, this is a real problem
  - hard to solve
- We could try to prove program equivalence
  - but automating this is very hard
  - undecidable problem

Korat: A way to generate tests

Use pre- and post-conditions to generate tests automatically

Problem Korat tackles:

- There are infinitely many tests
  - which finite subset should we pick?

- And even finite subsets can be too big
  - we need a subset which yields good coverage
  - without a lot of redundancy
    - many tests will just test the same thing
    - we need a way to select a diverse test suit

Small test case hypothesis:

If there exists a test that causes the program to fail, there exists a small test case that causes the program to fail.

If a list function works on lists of length 0, 1, 2, and 3, it probably works on all lists.

Korat’s insight

- Use the small test hypothesis
- We can often do a good job by testing all inputs up to a certain, small size

How do we generate test inputs?

```
class BinaryTree{
  Node root;
  class Node {
    Node left;
    Node right;
  }
}
```

- Use the types!
- The class declaration shows what values (or null) can fill each field
- Simply enumerate all possible shapes with a fixed set of Nodes.

A simple algorithm: put it all together

- User selects maximum input size k
- Generate all possible inputs up to size k
- Discard inputs where pre-condition is false
- Run the program on remaining inputs
- Check the results using the post-condition

Example: Binary Trees

- How many binary trees are there of size <= 3?

- 3 nodes
  - 2 slots per node (left and right)
  - 4 possible values (one of the nodes or null) for
    - each slot
    - the root

4 * (4 * 4)^3 = 2^14 = 16,384 possible trees

That’s a lot of trees!

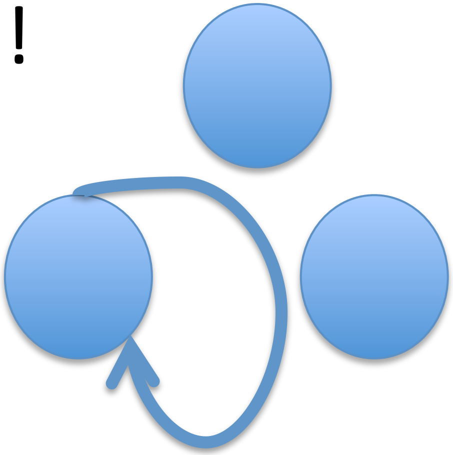
- The number of trees explodes rapidly
  > 1,000,000 trees of size <= 4
  > 16,000,000 trees of size <= 5

- Limits us to testing only very small input sizes

- Can we do better?

Actually, I lied

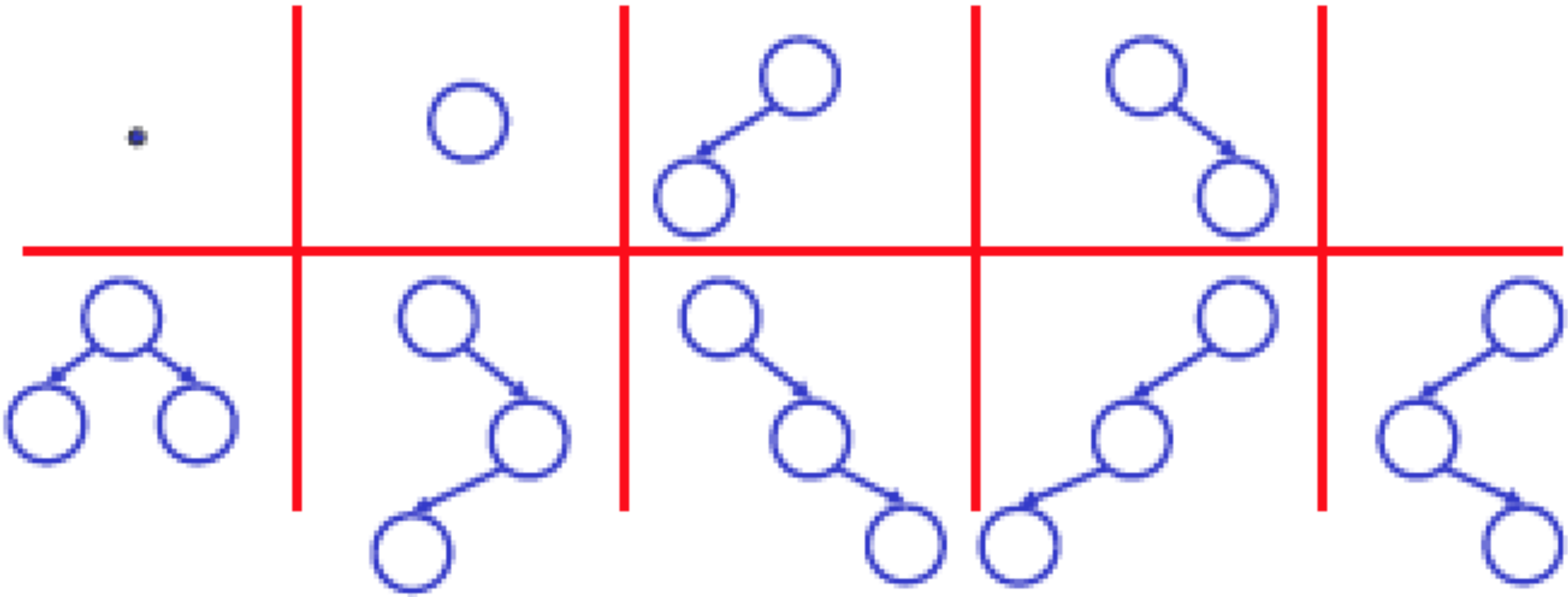
- 16,384 trees is a gross overestimate!
- Many of the shapes are not trees:



- Many trees are isomorphic

How many trees really?

- There are only 9 distinct binary trees on 3 or fewer nodes



Use our constraints to help us

- We want to avoid generating trees that don't satisfy the pre-condition in the first place.

- That means we must use the pre-condition to guide the generation of tests

- And use the constraints on distinctness of inputs

Observe the pre-condition

- Instrument the pre-condition
  - add code to observe it at runtime
  - in particular, record fields of the input the precondition accesses
- Observation:
  - if the pre-condition does not access a field, then the result of the pre-condition did not depend on that field.

Binary tree example

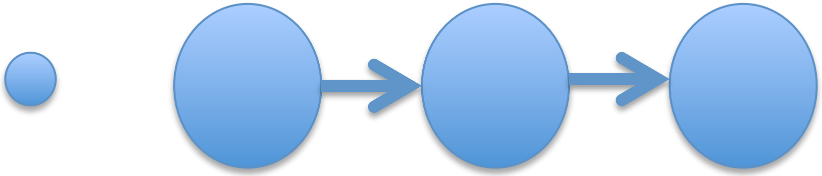
- Pre-condition checks
  - if the root is null

    return false
  - all nodes must be unique
    - no cycles
    - every node has one parent

    (except the root, which has 0)

Example:

- Consider the following “tree”



- The pre-condition accesses only the root
  - since the root is null, every possible shape for the other nodes would yield the same result

- This single input eliminates 25% of the tests

Karat enumerates the tests

- Start with the smallest
- Next test generated by
  - expanding a null pointer field
  - backtracking if all possibilities for a field are exhausted
- Never enumerate parts of input not examined by the precondition

Isomorphic tests

- We also want to avoid isomorphic tests
    - distinct trees with the same shape
- Number all objects within a type
- Number all fields
    - in the pre-condition access order
- When backtracking on field f
- Check if next object in ordering results in lexicographically least of structures of this shape

Error specifications

We can have two specifications:

- Normal behavior specification

- Error behavior specification

  under what circumstances exceptions are thrown

Korat Results

- Eliminating redundant tests is very effective
  - there are only 429 binary trees of size 7
  - infeasible to test on trees this large without the techniques for eliminating redundant tests
- Time to generate and run all tests usually seconds, sometimes minutes

Strengths

- Good for
  - linked data structures
  - small, easily specified procedures and methods
  - unit testing

Weaknesses (conditions)

Only as good as the pre- and post-conditions

Pre-condition: l.contains(x)

```
List remove(LinkedList l, Element x) {
  if (x == l.head())
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      new LinkedList(l.head(),remove(l.tail(), x));
}
```

Post-condition: !(l.contains(x)

Weaknesses (conditions)

Only as good as the pre- and post-conditions

Pre-condition: !(l.isEmpty())

```
List remove(LinkedList l, Element x) {
  if (x == l.head())
    return l.tail();
  else
    return
      new LinkedList(l.head(),remove(l.tail(), x));
}
```

Post-condition: l.isList()

Weaknesses (large data structures)

- Strong when we can enumerate all possibilities
  - four nodes, two edges per node
- Weaker when enumeration is weak
  - integers
  - floating point numbers
  - strings

Weakness (nondeterminism)

Not as good for nondeterministic methods

For example, what about a condition that says "Every packet sent is eventually acknowledged by the receiver"?

Test generation

- Automatic test generation is a good idea
- Types languages are a plus for generation
    - C++, Java, UML (C, Lisp do not provide needed types)
- Works well for unit tests
- Being adopted in industry
- Promising future