Generating Legal Test Inputs for Object-Oriented Programs

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M-TOOS'06

Automated Testing

- Goal: Automatically create a good test suite for an existing program with no specification
- Difficult
  - Complex object structures in programs are hard to create and test.
  - Specifications of object interaction are often not available.
- Our approach
  - Observe normal execution. Use information about actual call sequences to guide generation of tests.

Outline

- **Problem:** generating tests for complex structures
- **Technique**
  1. Create a model of legal calls / inputs
  2. Generate inputs using the model
- **Evaluation**
  - Test inputs for complex data structures
  - Coverage measurements
  - Observers as regression oracles
- **Conclusion**

Complex Test Inputs

- Test may require objects to be in certain states
- State can be defined by a sequence of mutator method calls

```
RoadMap m1 = new RoadMap();
m1.init();
City c1 = new City("Portland");
c1.setMap(m1);
m1.addCity(c1);
```

Not all call sequences make sense:

- Some calls are only valid in certain states
  - e.g., must call `init()` before adding cities
- Interdependencies between arguments and/or receivers
  - e.g., map must be set before city is added

Example: RoadMap

```
public class RoadMap {
  private Hashtable<City, Set<City>> cities;

  public static RoadMap genMap(){
    RoadMap m = new RoadMap();
    m.init(); return m;
  }

  public void init(){
    cities = new Hashtable<City,Set<City>>();
  }

  public void addCity(City c){
    cities.put(c, new HashSet<City>());
  }

  public void addRoad(City c1, City c2){
    addConnection(c1, c2);
    addConnection(c2, c1);
  }

  private void addConnection(City s, City t){
    cities.get(s).add(t);
  }

  public int numNeighbors (City c){
    return cities.get(c).size();
  }}
```

```
public class City {
  private RoadMap map;
  private String name;

  public City(String name){
     this.name = name;  }

  public void setMap(RoadMap m){
     this.map = m;  }

  public void addRoad(City c){
    map.addRoad(this, c); }

  public int numNeighbors(){
    return map.numNeighbors(this);  }
}
```

```
public static void main (String[] a) {
  RoadMap m1 = RoadMap.genMap();
  City c1 = new City(“Portland”);
  c1.setMap(m1);
  City c2 = new City(“Seattle”);
  c2.setMap(m1);
  m1.addCity(c1);
  m1.addCity(c2);
  c1.addRoad(c2);
  c1.numNeighbors();
}
```

State Space Is Huge

- The state space is too large for exhaustive techniques
- Random selection is unlikely to quickly find many valid test inputs
- Specifications of object interaction are often not available
- Realistic classes are far more complex

Outline

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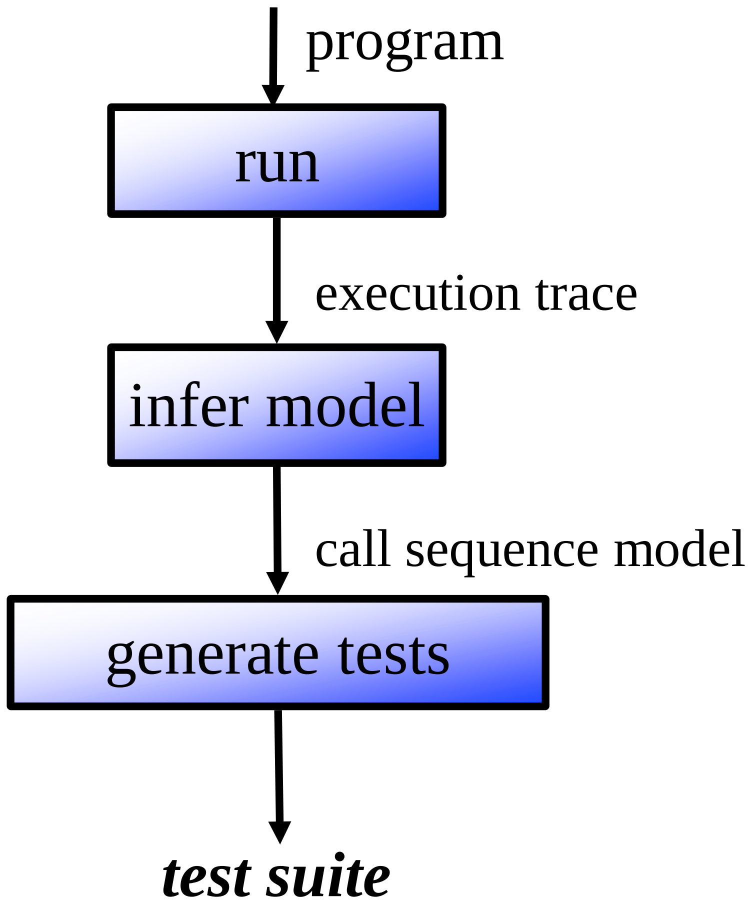
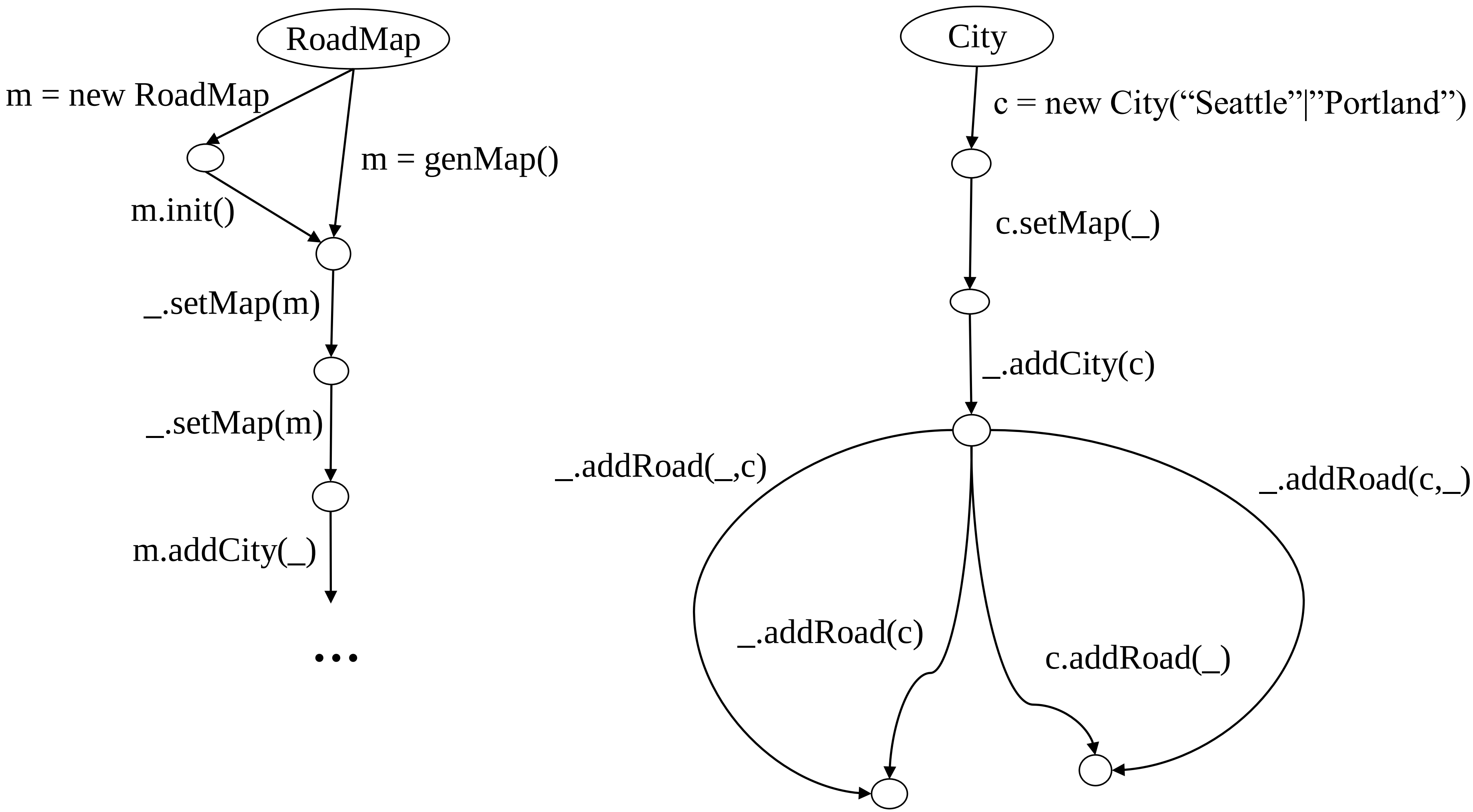
Technique


program
run
execution trace
infer model
call sequence model
generate tests
test suite

Call Sequence Graphs

- Models of legal call sequences
- One directed, rooted graph per class
  - nodes are collections of object states (describe histories of method calls)
  - edges are method calls (including String and primitive arguments)
- Paths from root are legal call sequences
- Graph over-approximates sequences observed during execution
  - includes additional paths
  - under-specifies method arguments

Model of the RoadMap example



Some values left unconstrained: _ = “don't care”

Inferring the Model

Steps:

1) Extract object histories from trace
   - Abstract away states for other objects
   - Filter out private and side-effect-free calls
2) Merge histories from objects of same class into a model for the class

Extracting Object Histories

Extract object histories from trace

- Abstract away states for other objects
- Filter out private and side-effect-free calls

```
m1 = genMap()
  m1 = new Map()
  m1.init()
c1 = new City("Portland")
c1.setMap(m1)
c2 = new City("Seattle")
c2.setMap(m1)
m1.addCity(c1)
m1.addCity(c2)
c1.addRoad(c2)
  m1.addRoad(c1,c2)
    m1.addConnection(c1,c2)
    m1.addConnection(c2,c1)
c1.numNeighbors()
```

execution trace

nested calls

Extracting Object Histories

Extract object histories from trace

- Abstract away states for other objects
- Filter out private and side-effect-free calls

```
m1 = genMap()
  m1 = new Map()
  m1.init()
c1 = new City("Portland")
c1.setMap(m1)
c2 = new City("Seattle")
c2.setMap(m1)
m1.addCity(c1)
m1.addCity(c2)
c1.addRoad(c2)
  m1.addRoad(c1,c2)
    m1.addConnection(c1,c2)
    m1.addConnection(c2,c1)
c1.numNeighbors()
```

Example: extracting history for **c1**

← Calls involving **c1**

Extracting Object Histories

Extract object histories from trace

- Abstract away states for other objects
- Filter out private and side-effect-free calls

```
m1 = genMap()
  m1 = new Map()
  m1.init()
c1 = new City("Portland")
c1.setMap(m1)
c2 = new City("Seattle")
c2.setMap(m1)
m1.addCity(c1)
m1.addCity(c2)
c1.addRoad(c2)
  m1.addRoad(c1,c2)
    m1.addConnection(c1,c2)
    m1.addConnection(c2,c1)
c1.numNeighbors()
```

→

```
c1 = new City("Portland")
c1.setMap(m1)
m1.addCity(c1)
c1.addRoad(c2)
  m1.addRoad(c1,c2)
    m1.addConnection(c1,c2)
    m1.addConnection(c2,c1)
c1.numNeighbors()
```

Extracting Object Histories

Extract object histories from trace

- Abstract away states for other objects
- Filter out private and side-effect-free calls

```
m1 = genMap()
  m1 = new Map()
  m1.init()
c1 = new City("Portland")
c1.setMap(m1)
c2 = new City("Seattle")
c2.setMap(m1)
m1.addCity(c1)
m1.addCity(c2)
c1.addRoad(c2)
  m1.addRoad(c1,c2)
    g1.addConnection(c1,c2)
    g1.addConnection(c2,c1)
c1.numNeighbors()
```

```
c1 = new City("Portland")
c1.setMap(_)
_.addCity(c1)
c1.addRoad(_)
  _.addRoad(c1,_)
     _.addConnection(c1,_)
     _.addConnection(_,c1)
c1.numNeighbors()
```

Extracting Object Histories

Extract object histories from trace

- Abstract away states for other objects
- Filter out private and side-effect-free calls

```
m1 = genMap()
  m1 = new Map()
  m1.init()
c1 = new City("Portland")
c1.setMap(m1)
c2 = new City("Seattle")
c2.setMap(m1)
m1.addCity(c1)
m1.addCity(c2)
c1.addRoad(c2)
  m1.addRoad(c1,c2)
    g1.addConnection(c1,c2)
    g1.addConnection(c2,c1)
c1.numNeighbors()
```

```
c1 = new City("Portland")
c1.setMap(_)
_.addCity(c1)
c1.addRoad(_)
  _.addRoad(c1,_)
    _.addConnection(c1,_)
    _.addConnection(_,c1)
c1.numNeighbors()
```

private

side-effect free

Extracting Object Histories

object history for c1

```
c1 = new City("Portland")
c1.setMap(_)
_.addCity(c1)
c1.addRoad(_)
   _.addRoad(c1,_)
```

object history for c2

```
c2 = new City("Seattle")
c2.setMap(_)
_.addCity(c2)
_.addRoad(c2)
   _.addRoad(_,c2)
```

Merging Object Histories

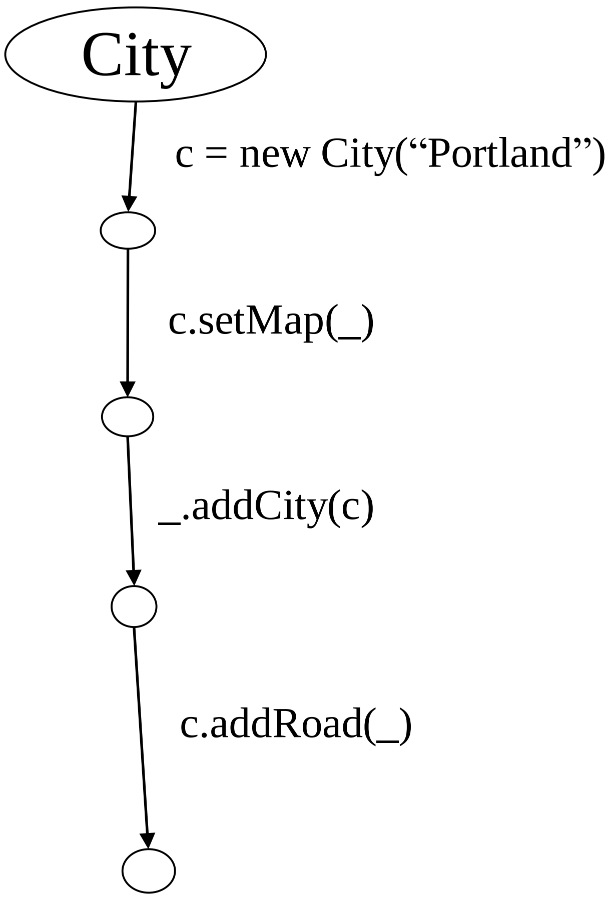
- Incrementally incorporate histories into the models
- When adding an object history:
  - Merge prefixes (reuse existing nodes and edges)
  - Record primitives and Strings passed as parameters
  - Add nested calls as alternative paths

Merging: example

```
c = new City("Portland")
c.setMap(_)
_.addCity(c)
c.addRoad(_)
   _.addRoad(c,_)
```

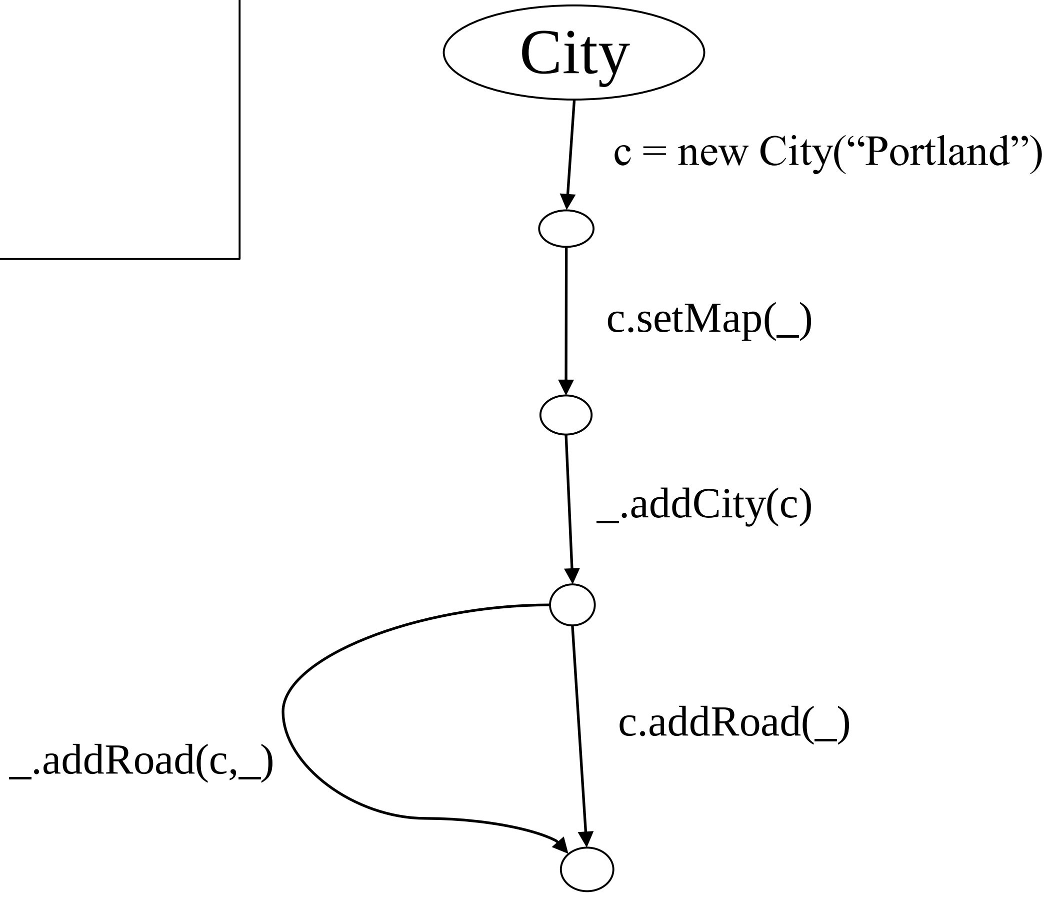
Merging: example

c = new City("Portland")
c.setMap(_)
_.addCity(c)
c.addRoad(_)
.addRoad(c,)



Merging: example

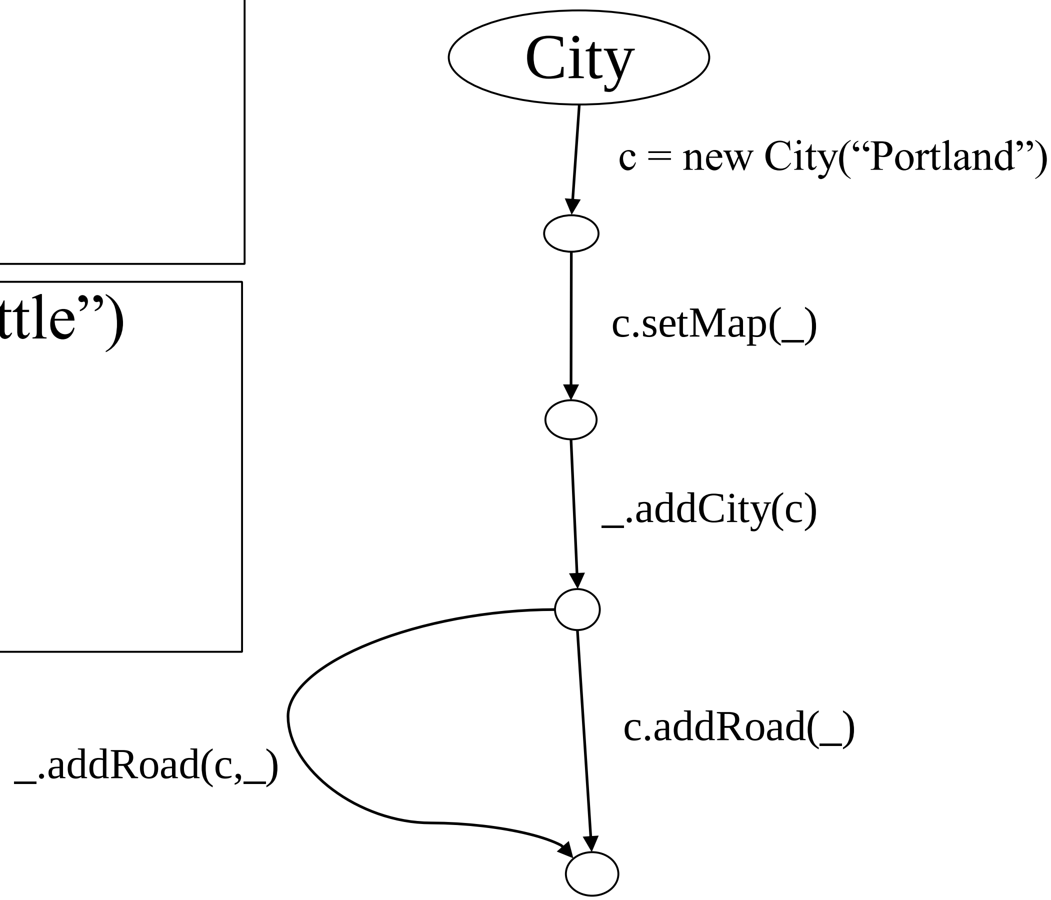
```
c = new City("Portland")
c.setMap(_)
_.addCity(c)
c.addRoad(_)
   _.addRoad(c,_)
```



Merging: example

```
c = new City("Portland")
c.setMap(_)
_.addCity(c)
c.addRoad(_)
  _.addRoad(c,_)
```

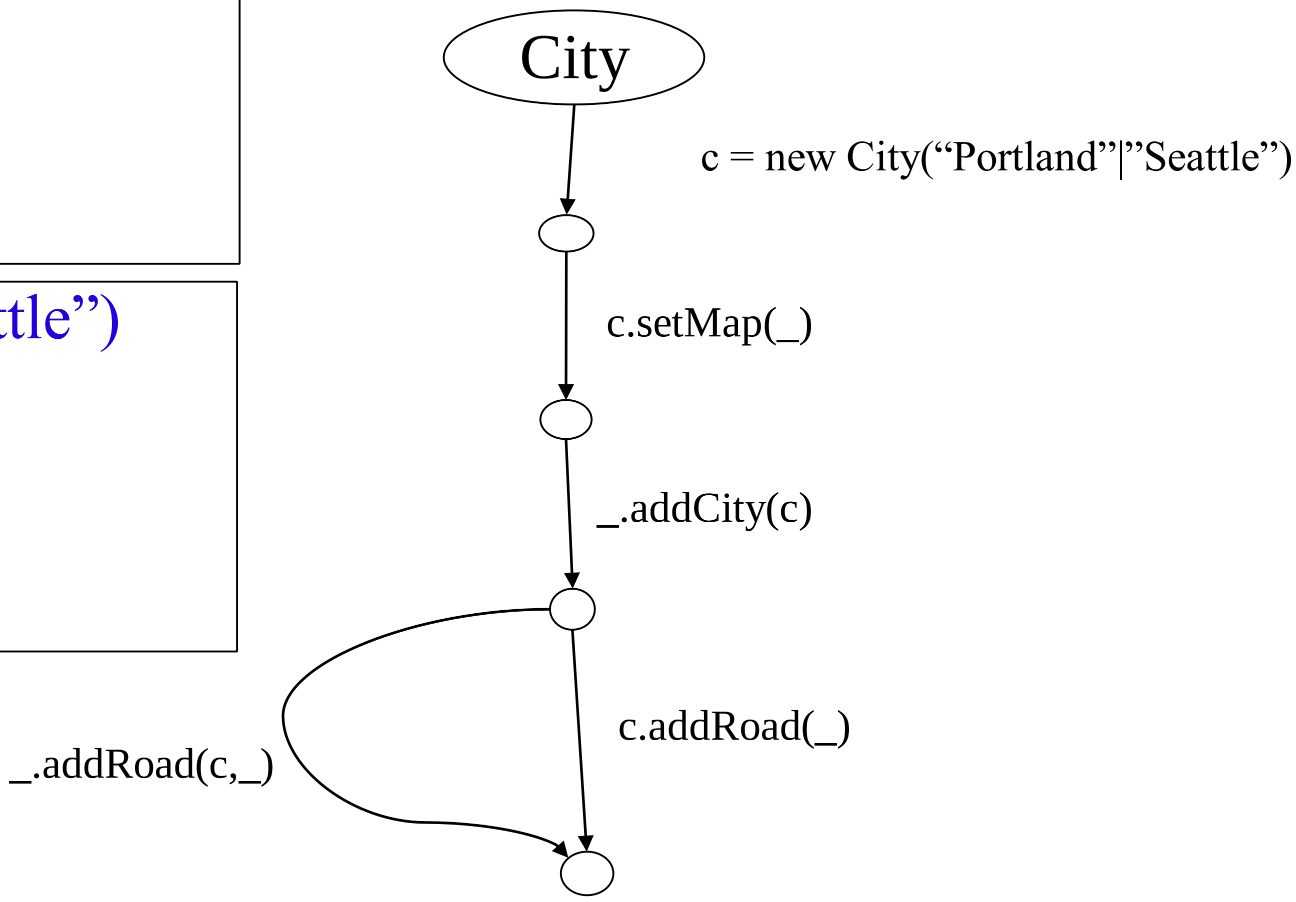
```
c = new City("Seattle")
c.setMap(_)
_.addCity(c)
_.addRoad(c)
  _.addRoad(_,c)
```



Merging: example

c = new City(“Portland”)
c.setMap(_)
_.addCity(c)
c.addRoad(_)
    .addRoad(c,)

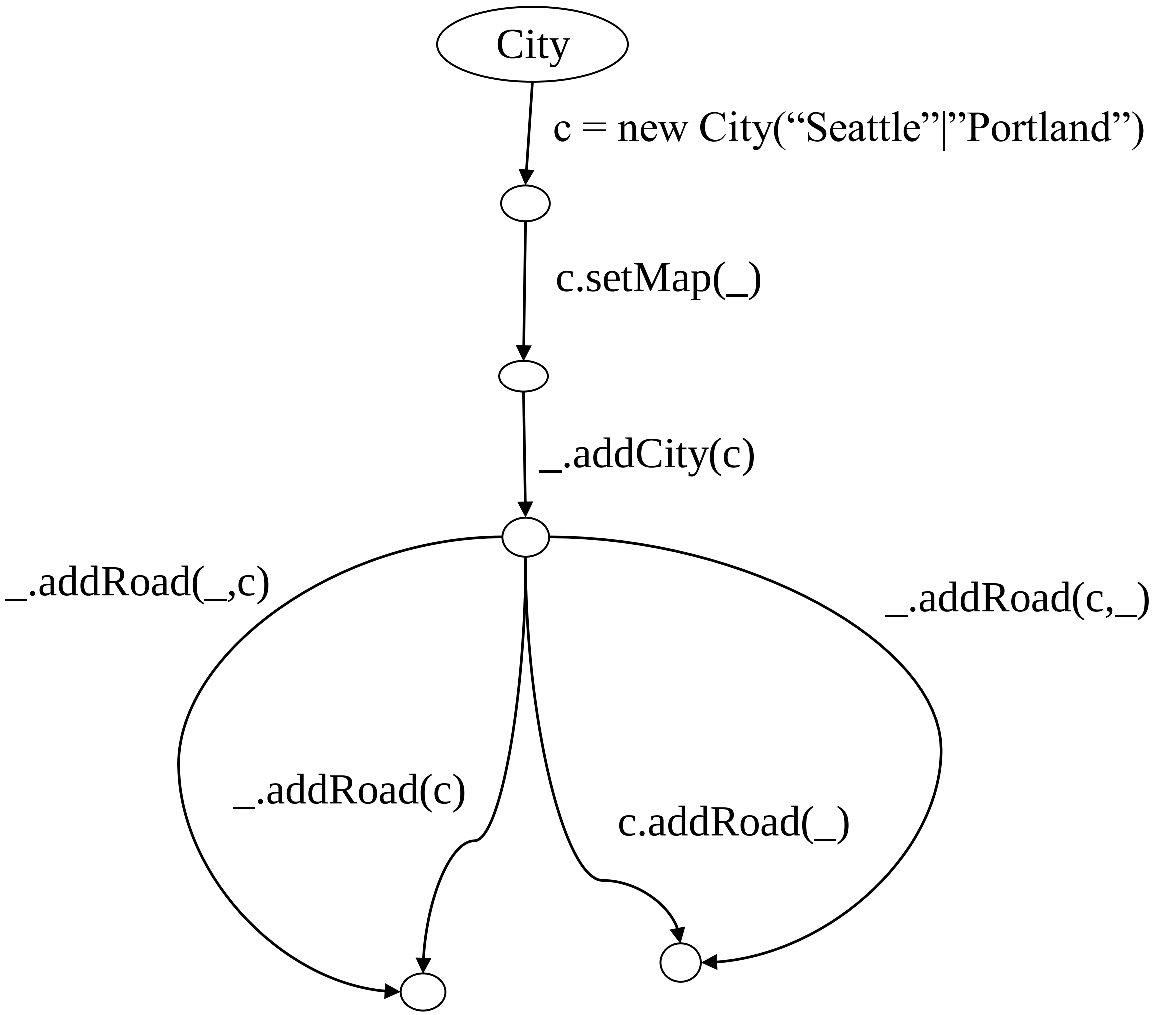
c = new City(“Seattle”)
c.setMap(_)
_.addCity(c)
_.addRoad(c)
    .addRoad(,c)



Merging: example

```
c = new City("Portland")
c.setMap(_)
_.addCity(c)
c.addRoad(_)
   _.addRoad(c,_)
```

```
c = new City("Seattle")
c.setMap(_)
_.addCity(c)
_.addRoad(c)
   _.addRoad(_,c)
```



Outline

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Test Input Generator

Two Phases:

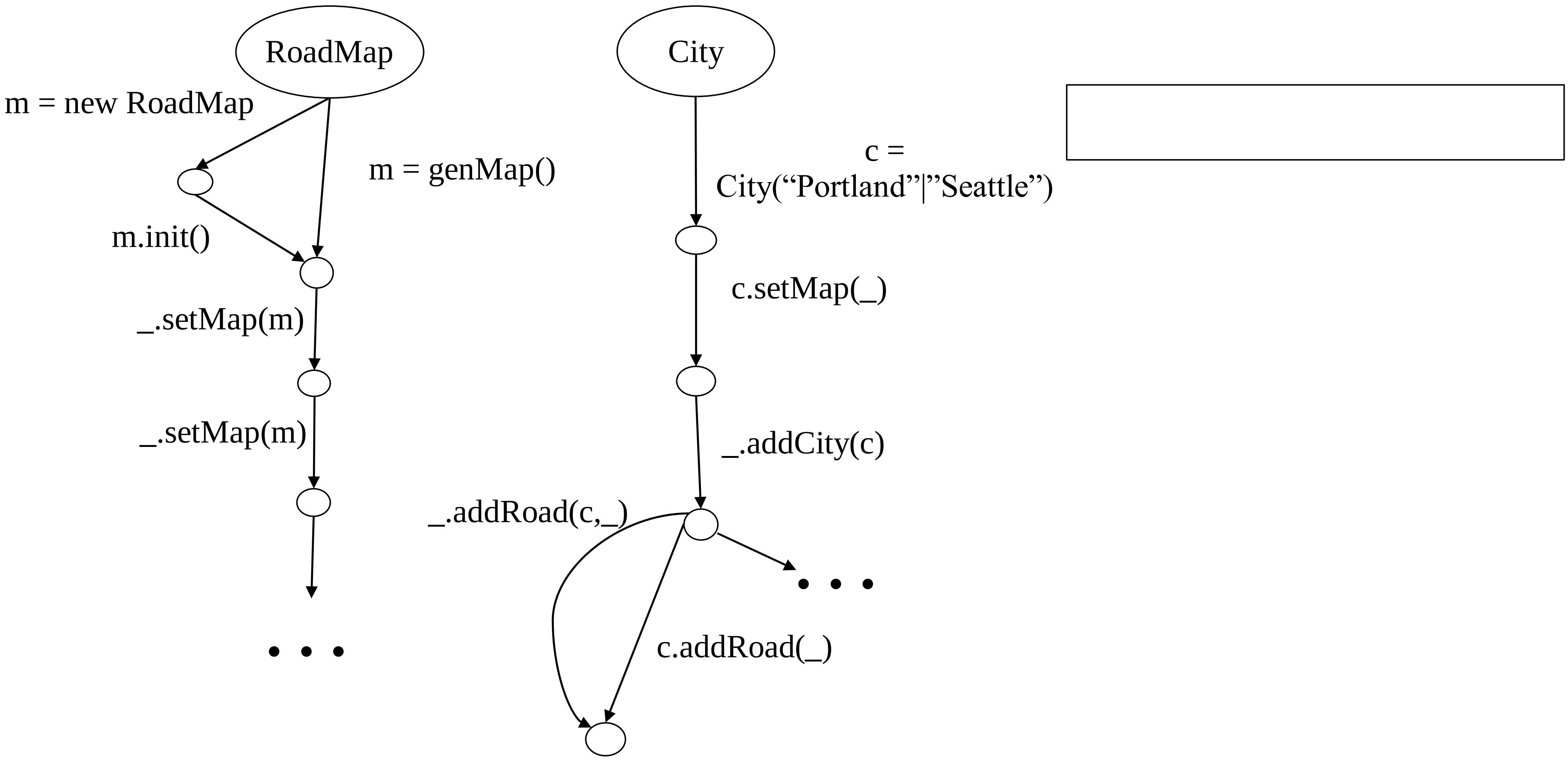
1. Random Generation
   - Allows calling methods not observed during execution
   - Generates random sequences of method calls

2. Model-Based Generation
   - Model is under-constrained
     - Alternative paths in model
     - Underspecified method arguments

   - Generation is randomized: faced with a choice, generator picks one randomly

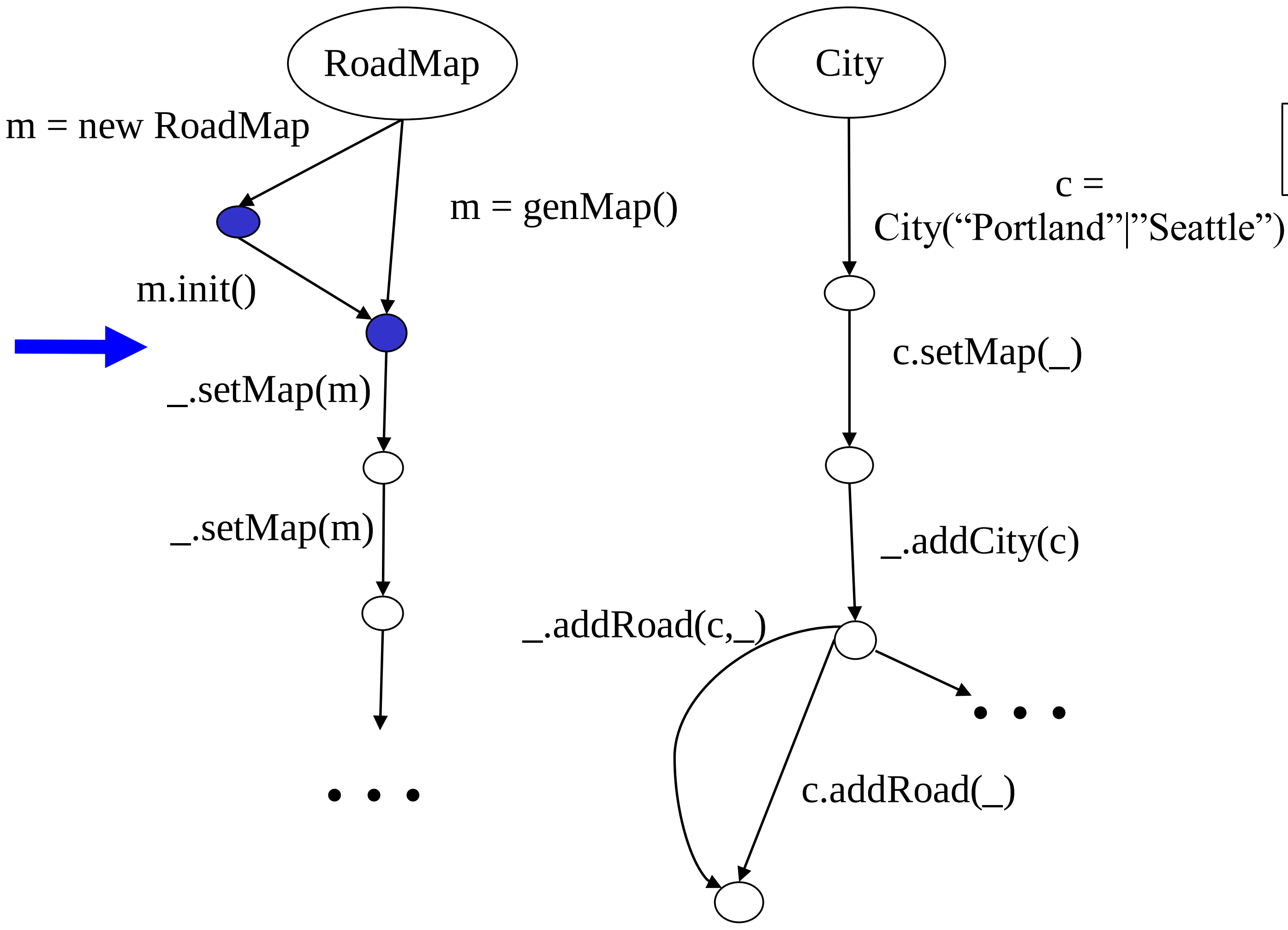
Model-Based Input Generator

Example: generate a test input for RoadMap



Model-Based Input Generator

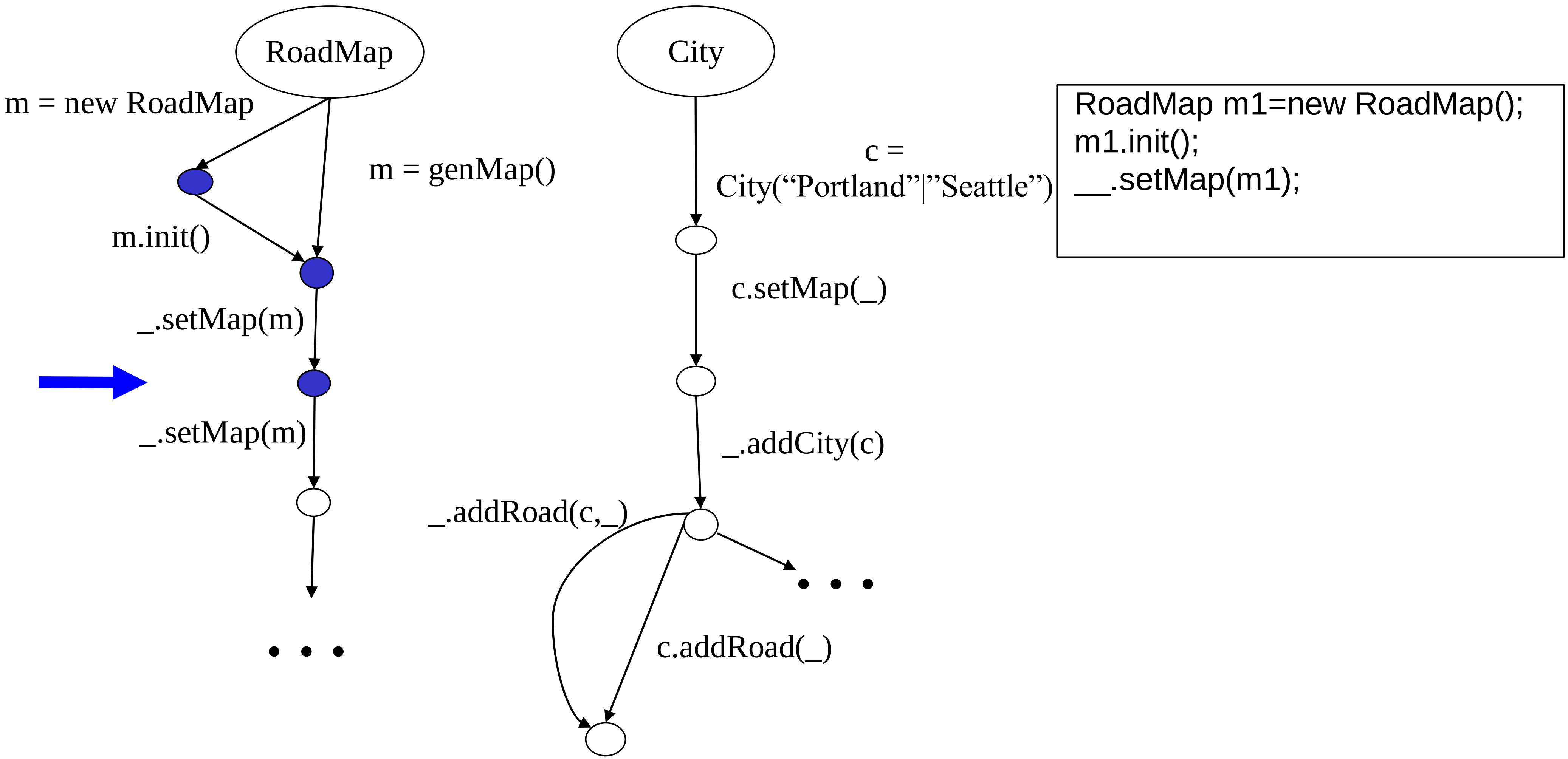
Example: generate a test input for RoadMap




```
RoadMap m1=new RoadMap();
m1.init();
```

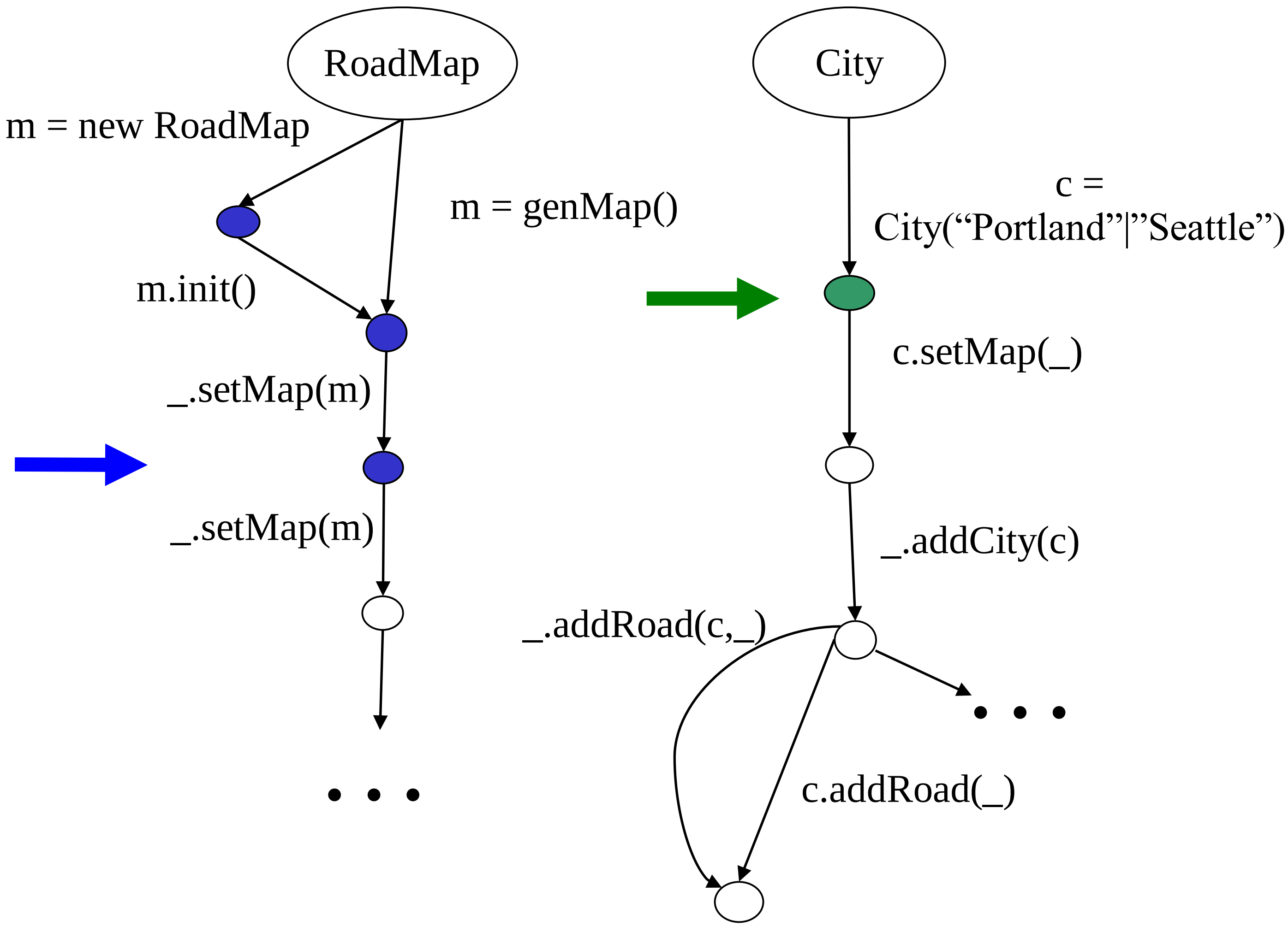
Model-Based Input Generator

Example: generate a test input for RoadMap



Model-Based Input Generator

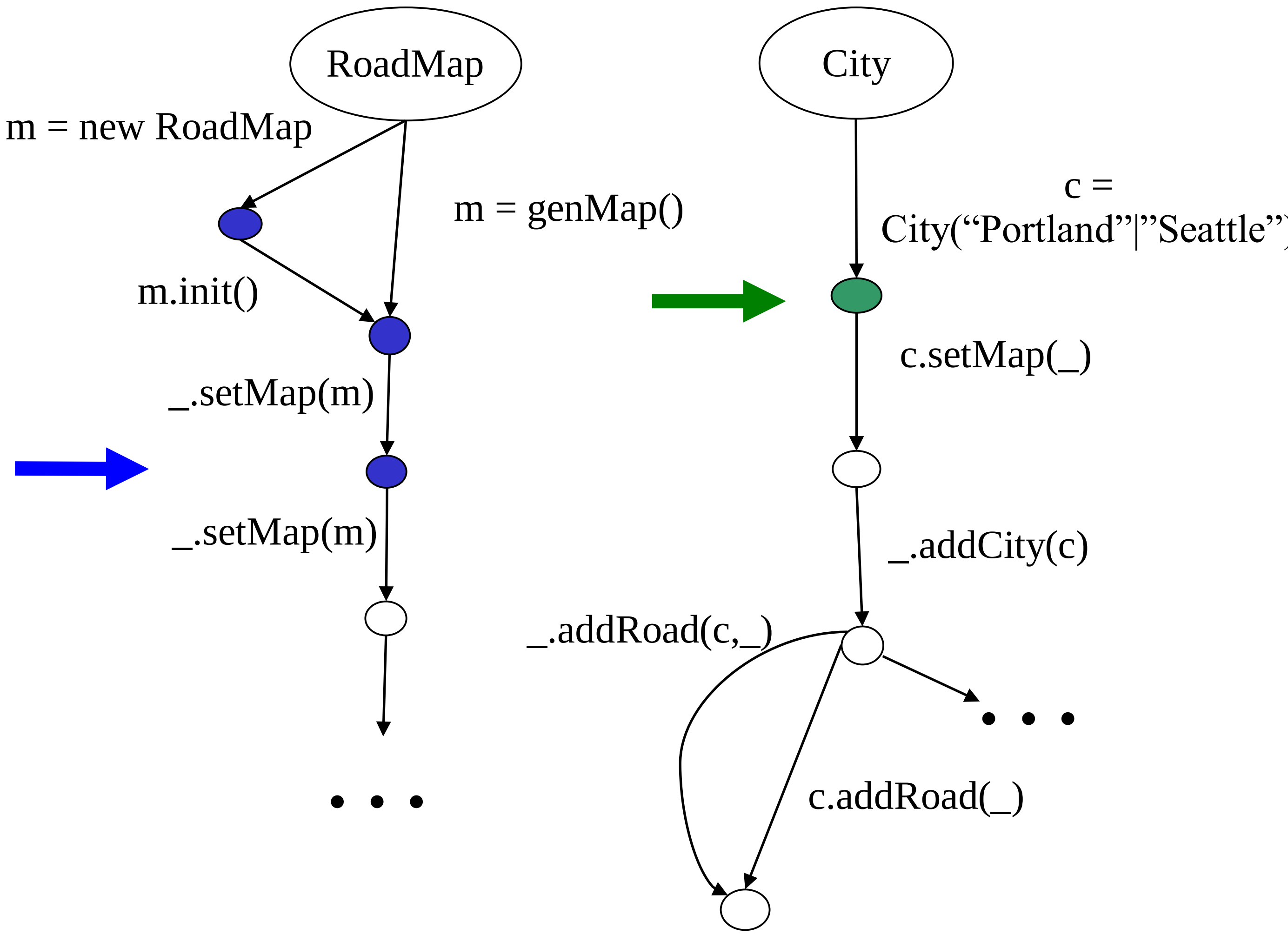
Example: generate a test input for RoadMap



RoadMap m1=new RoadMap();
m1.init();
__.setMap(m1);

Model-Based Input Generator

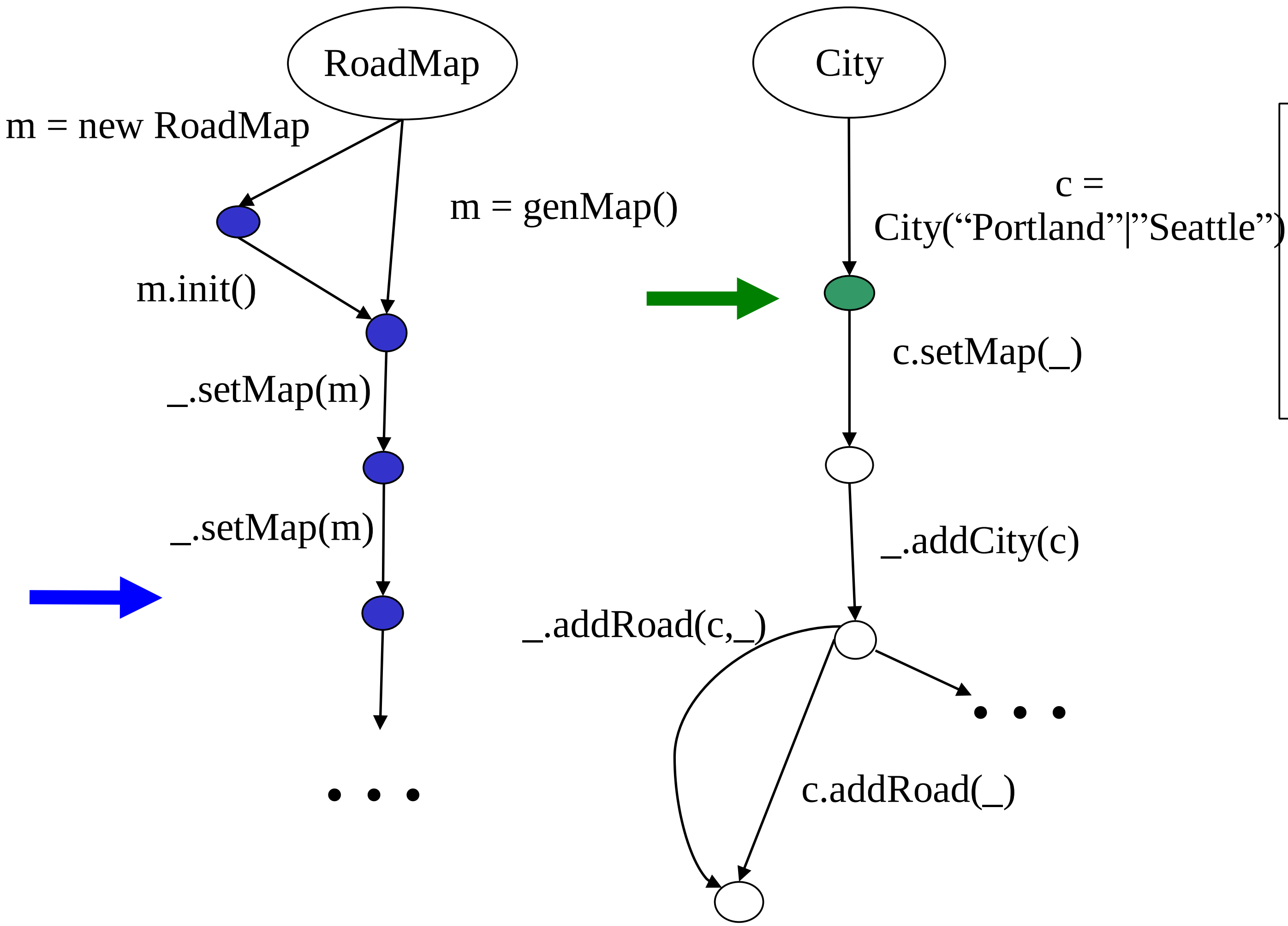
Example: generate a test input for RoadMap



RoadMap m1=new RoadMap();
m1.init();
City c1=new City(“Seattle”);
c1.setMap(m1);

Model-Based Input Generator

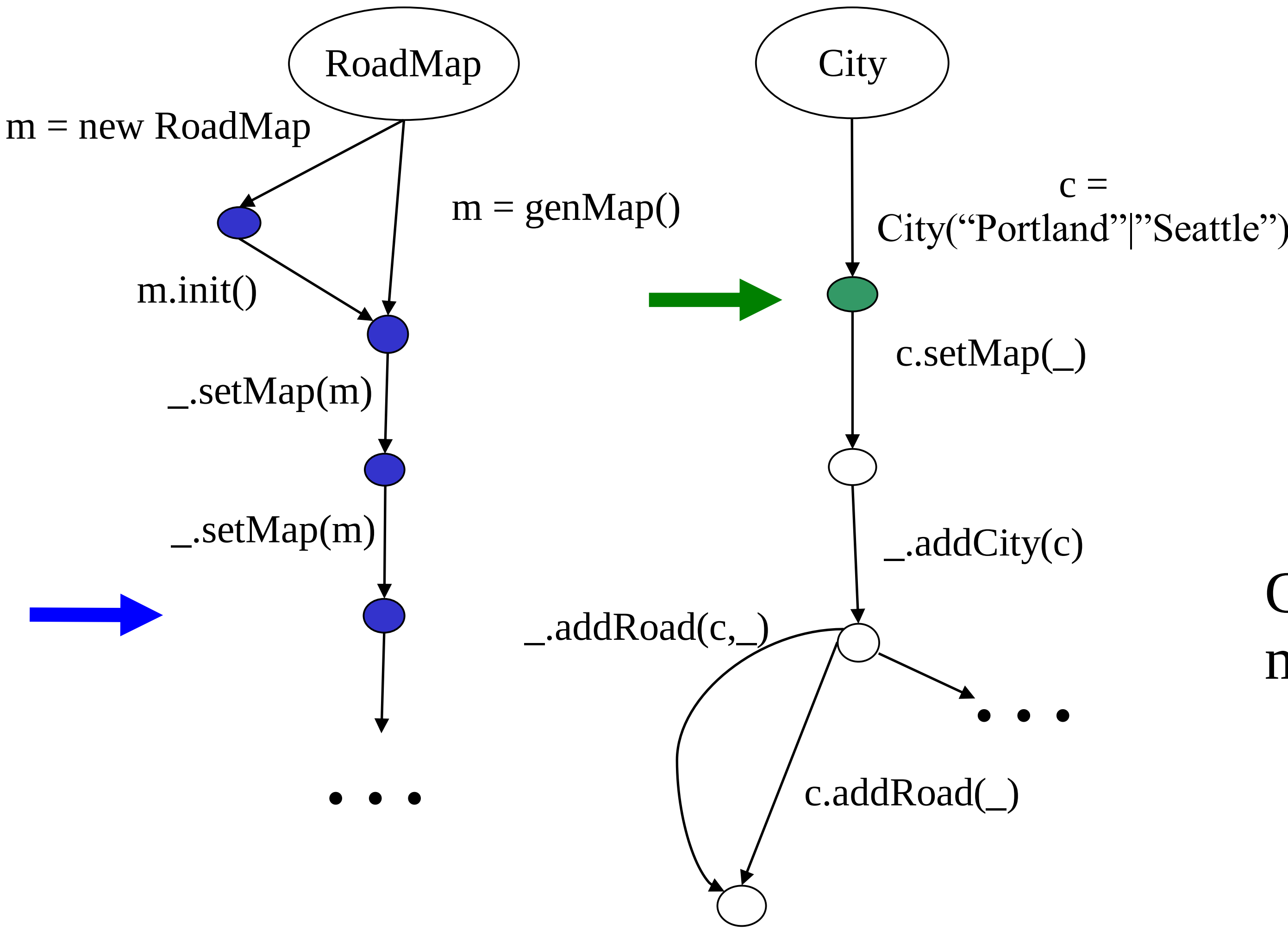
Example: generate a test input for RoadMap




```
RoadMap m1=new RoadMap();
m1.init();
City c1=new City("Seattle");
c1.setMap(m1);
_.setMap(m1);
```

Model-Based Input Generator

Example: generate a test input for RoadMap




```
RoadMap m1=new RoadMap();
m.init();
City c1=new City("Seattle");
c1.setMap(m1);
c1.setMap(m1);
```

Generation is randomized--
may insert redundant calls

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Evaluation: creating complex inputs

- Daikon invariant detector (ca 185 kLOC)
  - Internal data structures constructed and used in very specific ways
  - Static type information is not enough to generate valid structures
  - Example: LinearBinaryCore

Creating a valid LinearBinaryCore

```
VarInfoName name_x = VarInfoName.parse("x");
VarInfoName name_y = VarInfoName.parse("y");
VarInfoName name_z = VarInfoName.parse("z");

ProglangType int_type = ProglangType.parse("int");            //string must denote a type
ProglangType file_rep_type = ProglangType.rep_parse("int");   //string must denote a type
ProglangType rep_type = file_rep_type.fileTypeToRepType();    //required call

VarInfoAux aux = VarInfoAux.parse("");

VarComparability comp = VarComparability.parse(0, "22", int_type);   //param "22" must be a number

VarInfo v1 = new VarInfo(name_x, int_type, rep_type, comp, aux);
VarInfo v2 = new VarInfo(name_y, int_type, rep_type, comp, aux);
VarInfo v3 = new VarInfo(name_z, int_type, rep_type, comp, aux);

VarInfo[] ppt_vis = new VarInfo[] {v1, v2, v3};
VarInfo[] slice_vis = new VarInfo[] {v1, v2};                 //must be a 2-elem subset of ppt_vis

PptTopLevel ppt = new PptTopLevel
  ("DataStructures.StackAr.StackAr(int):::EXIT33", ppt_vis);   //string must be in a specific format

PptSlice2 slice = new PptSlice2(ppt, slice_vis);
Invariant proto = LinearBinary.get_proto();
Invariant inv = proto.instantiate(slice);

LinearBinaryCore lbc = new LinearBinaryCore(inv); //one of 2 specific subtypes of Invariant (299 total)
```

- At every step, there are hundreds of other possible calls
- Our tool was able to create 3 different, legal, LinearBinaryCores in 10 seconds

Example automatically-generated `LinearBinaryCore`

```
VarInfoName name1 = VarInfoName.parse("return");
VarInfoName name2 = VarInfoName.parse("return");
ProglangType type1 = ProglangType.parse("int");
ProglangType type2 = ProglangType.parse("int");

VarInfoAux aux1 = VarInfoAux.parse(" declaringClassPackageName=, ");
VarInfoAux aux2 = VarInfoAux.parse(" declaringClassPackageName=, ");
VarComparability comp1 = VarComparability.parse(0, "22", type1);
VarComparability comp2 = VarComparability.parse(0, "22", type2);
VarInfo v1 = new VarInfo(name1, type1, type1, comp1, aux1);
VarInfo v2 = new VarInfo(name2, type2, type2, comp2, aux2);

VarInfo[] vs = new VarInfo[] {v1, v2};

PptTopLevel ppt1 = new PptTopLevel("StackAr.push(Object):::EXIT", vs);

PptSlice slice1 = ppt1.gettempslice(v1, v2);
Invariant inv1 = LinearBinaryCore.getproto();
Invariant inv2 = inv1.instantiate(slice1);
LinearBinaryCore lbc = new LinearBinaryCore(inv2);
```

Coverage Experiment

- Experiment
  - 4 subject programs (11-98 kLOC)
  - Measured block coverage achieved
    - using our model-based approach, vs
    - random generation
- Results
  - Model-based generation improved coverage 6% to 68%
  - Largest improvement for programs with more constrained interfaces.

Regression Experiment

- Experiment: MIT 6.170 assignment, 143 students
- Existing staff solution and staff-written test suite

- Regression oracle: fail if exception or different values returned by observer methods (using staff solution as reference implementation).
- We compared generated suite to suite written by course staff.

- Results: generated test suite caught 4.5 times more faulty implementations than staff-written one
  - Staff-written suite detects 14 faulty implementations
  - Generated suite detects 63
  - Randomly generated suite detects 41

Next Steps

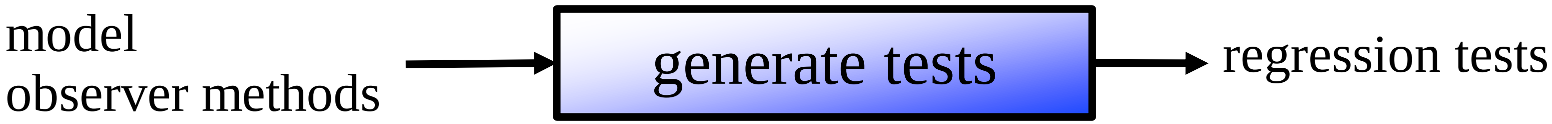
- Compare to exhaustive testing techniques (software model checking)
- Categorize programs on which the technique works best
- Investigate enhancing the models with additional constraints on object states
- Investigate using the models in anomaly detection

Contributions

- Created a model-based technique for automatic creation of test suites from a run of a program.
- Our tool created valid inputs for a complex data structure from a large application.
- Using our tool improves coverage of test suites.
- In our experiment, generated suite had almost 5 times better error detection than suite written by hand (and minimal false-positive rate).

Additional Slides

Creating regression tests



Two-step process:

1) Generate test inputs from model

Explores model; uses randomization

2) Create a regression oracle for each input

Uses observer methods

input + regression oracle = regression test

Generating a regression oracle

- Given: a newly-created input
- Goal: create a regression oracle for input
  - Execute input
  - Call observer methods on resulting objects
  - Record return values

```
Map m = new Map();
m.init();
City c = new City("Seattle");
c.setMap(m);
c.setMap(m);
City c2 = new City("Portland");
c2.setMap(m);

assertTrue(m.numCities() == 2);
assertTrue(c.numNeighbors() == 0);
assertTrue(c2.numNeighbors() == 0);
```