Combined Static and Dynamic Automated Test Generation

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Unit Testing for Object-oriented Programs

- **Unit test = sequence of method calls + testing oracle**

- Automated test generation is **challenging**:
  - **Legal** sequences for constrained interfaces
  - **Behaviorally-diverse** sequences for good coverage
  - **Testing oracles** (**assertions**) to detect errors

Unit Testing a Database Program

```
public void testConnection() {
    Driver driver = new Driver();

    Connection connection =
        driver.connect("jdbc:tinysql");
    Statement s = connection.createStmt();
    s.execute("create table test (name char(25))");
    ....
    s.close();
    connection.close();
}
```

① ➡ driver.connect("jdbc:tinysql");
② ➡ Statement s = connection.createStmt();
③ ➡ s.execute("create table test (name char(25))");

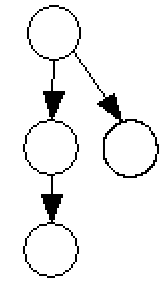
Constraint 1:
Method-call orders

Constraint 2:
Argument values

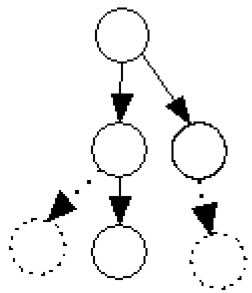
It is hard to create tests automatically!

Palus: Combining Dynamic and Static Analyses

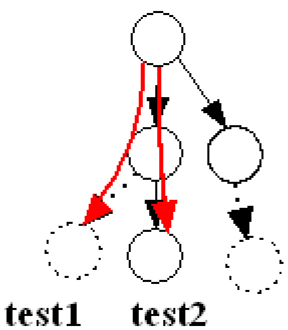
- **Dynamically infer an object behavior model from a sample (correct) execution trace**
  - Capture method-call order and argument constraints



- **Statically identify related methods**
  - **Expand** the (incomplete) dynamic model



- **Model-Guided random test generation**
  - Fuzz along a specific legal path

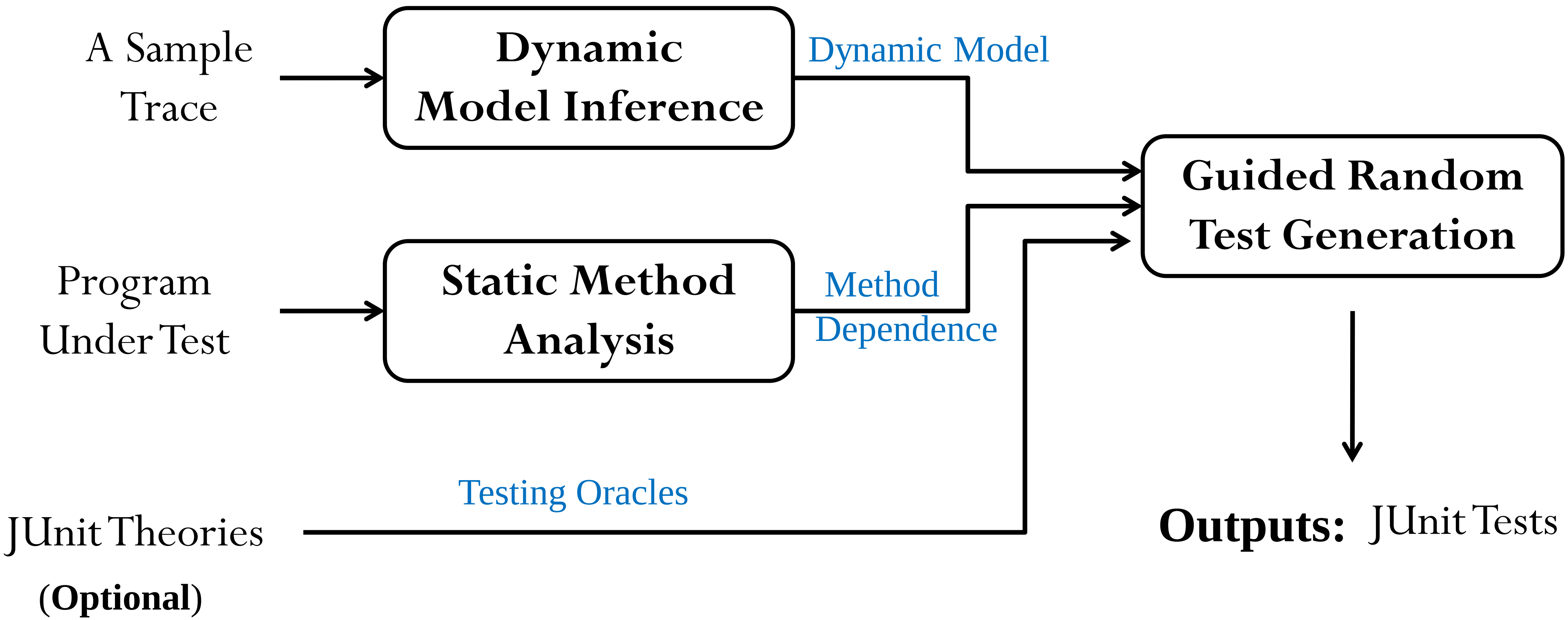


Outline

- Motivation
- Approach
  - Dynamic model inference
  - Static model expansion
  - Model-guided test generation
- Evaluation
- Related Work
- Conclusion and Future Work

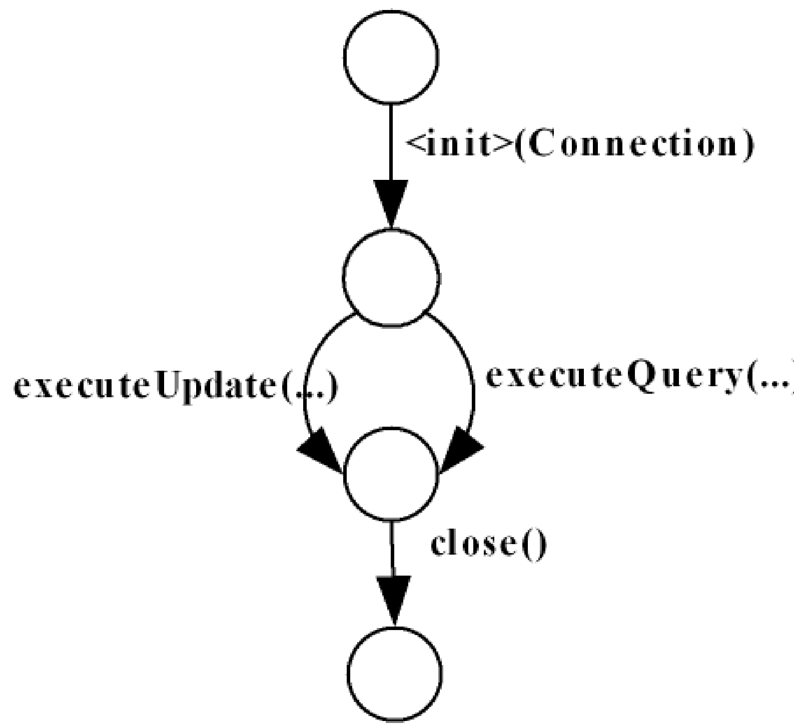
Overview of the Palus approach

Inputs:



(1) Dynamic Model Inference

- Infer a ***call sequence model*** for each tested class
  - Capture **possible ways** to create legal sequences
- A ***call sequence model***
  - A **rooted**, **acyclic** graph
  - **Node**: object state
  - **Edge**: method-call
  - One model **per class**



class Statement

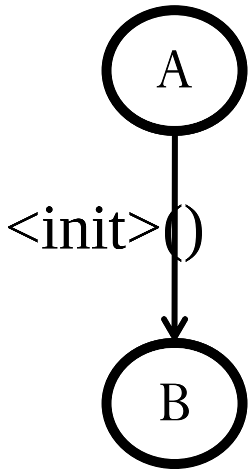
An Example Trace for Model Inference

```
Driver d = new Driver()
Connection con = driver.connection(“jdbc:dbname”);

Statement stmt1 = new Statement(con);
stmt1.executeQuery(“select * from table_name”);
stmt1.close();

Statement stmt2 = new Statement(con);
stmt2.executeUpdate(“drop table table_name”);
stmt2.close();

con.close();
```

Model Inference for class `Driver`

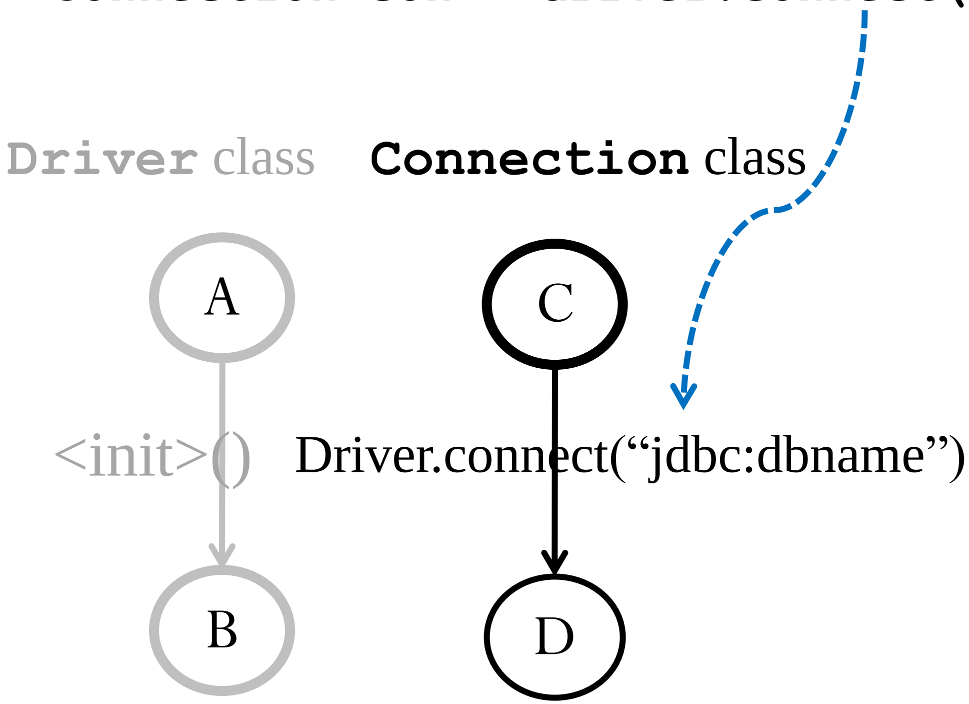
```
Driver d = new Driver();
```

`Driver` class



Model Inference for class `Connection`

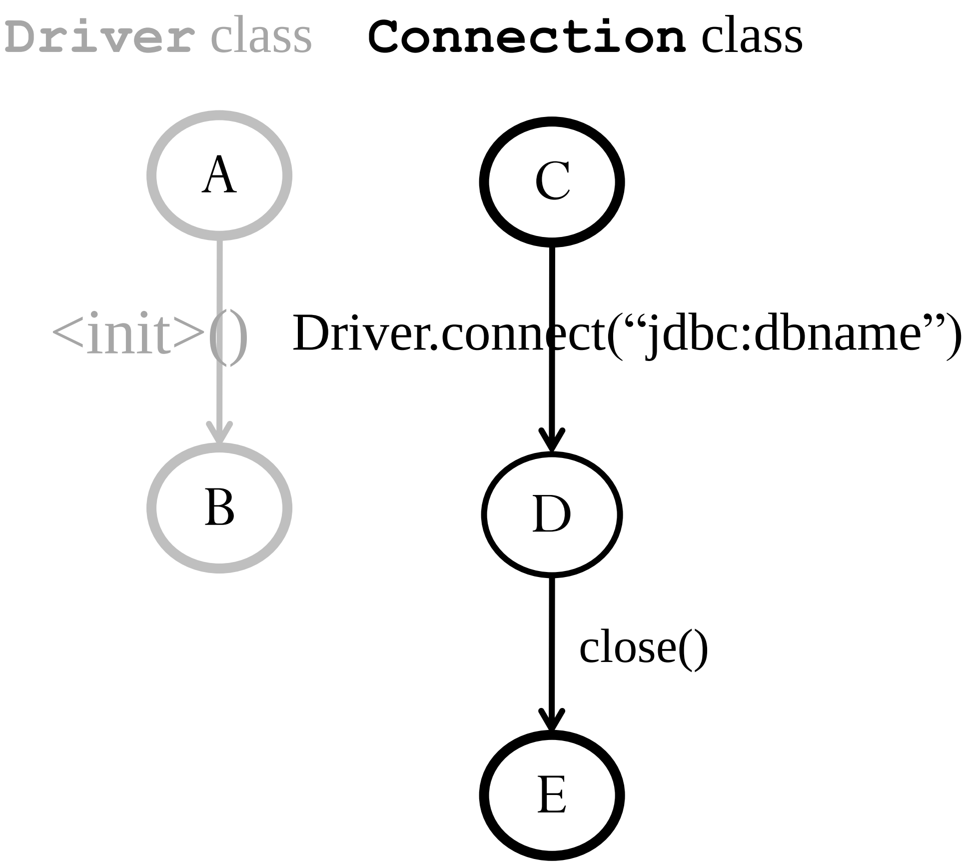
```
Connection con = driver.connect("jdbc:dbname");
```



 Nested calls are omitted for brevity

Model Inference for class `Connection`

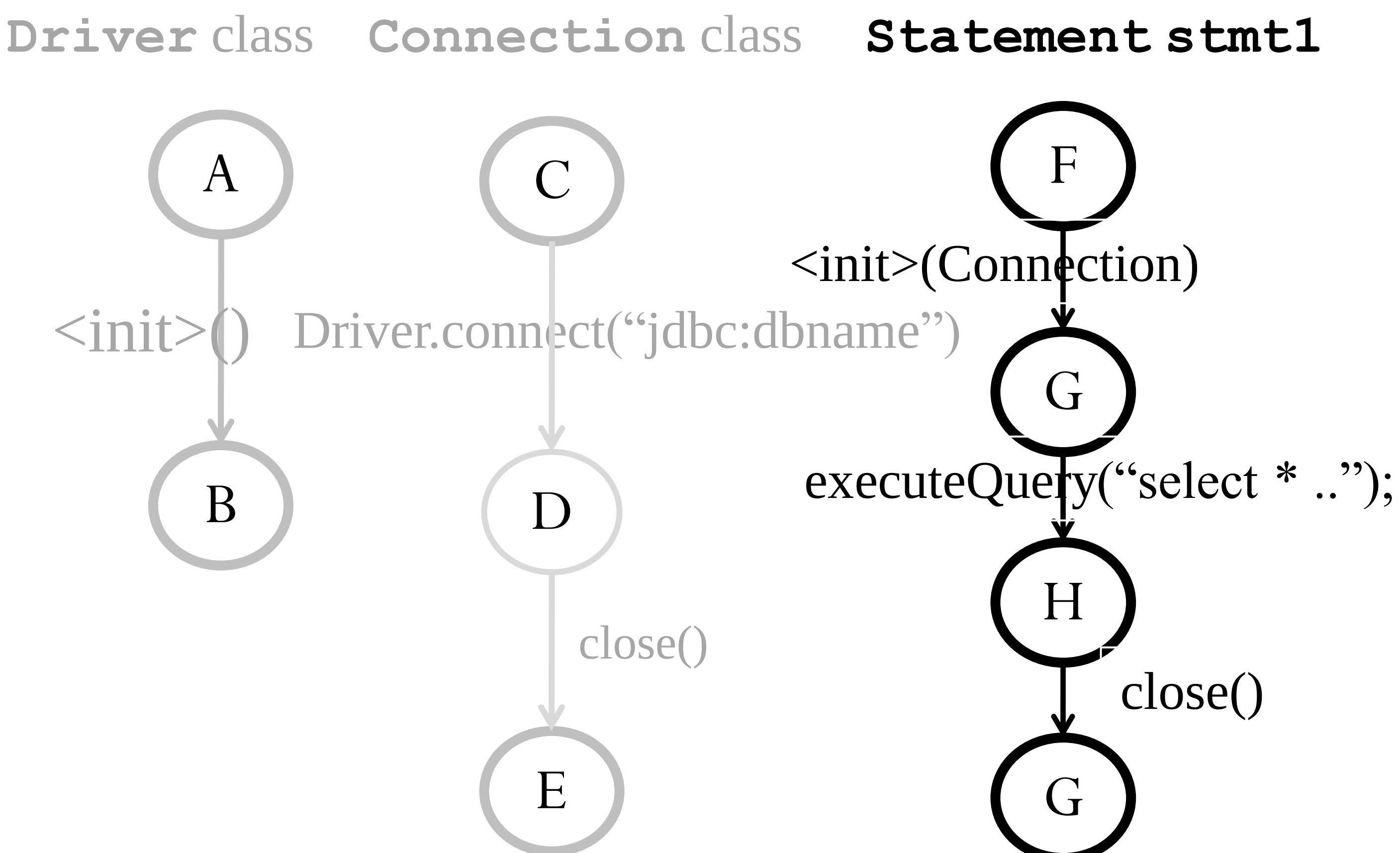
```
Connection con = driver.connect("jdbc:dbname");
con.close();
```



Nested calls are omitted for brevity

Model Inference for class `Statement`

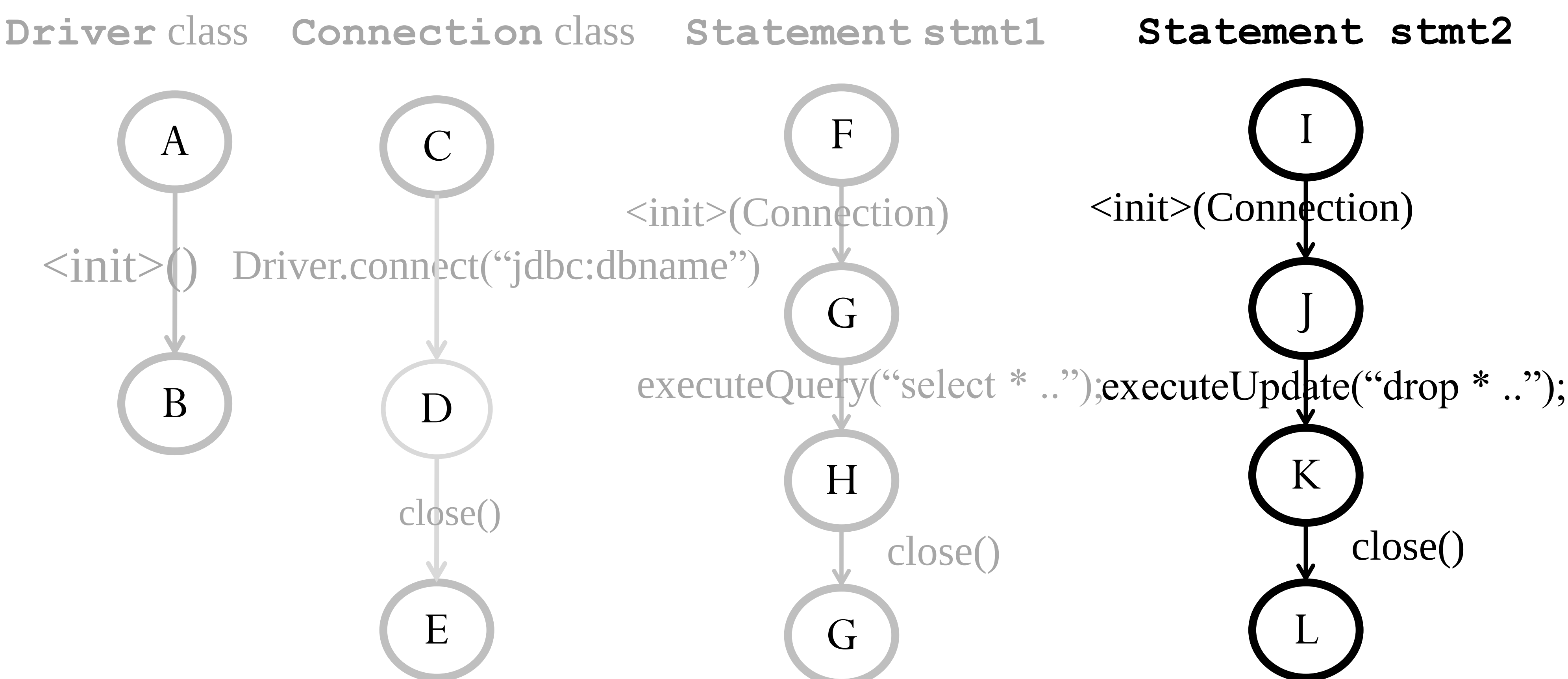
```
Statement stmt1 =  new Statement(con);
stmt1.executeQuery("select * from table_name");
stmt1.close();
```



Construct a call sequence model for each **observed object**

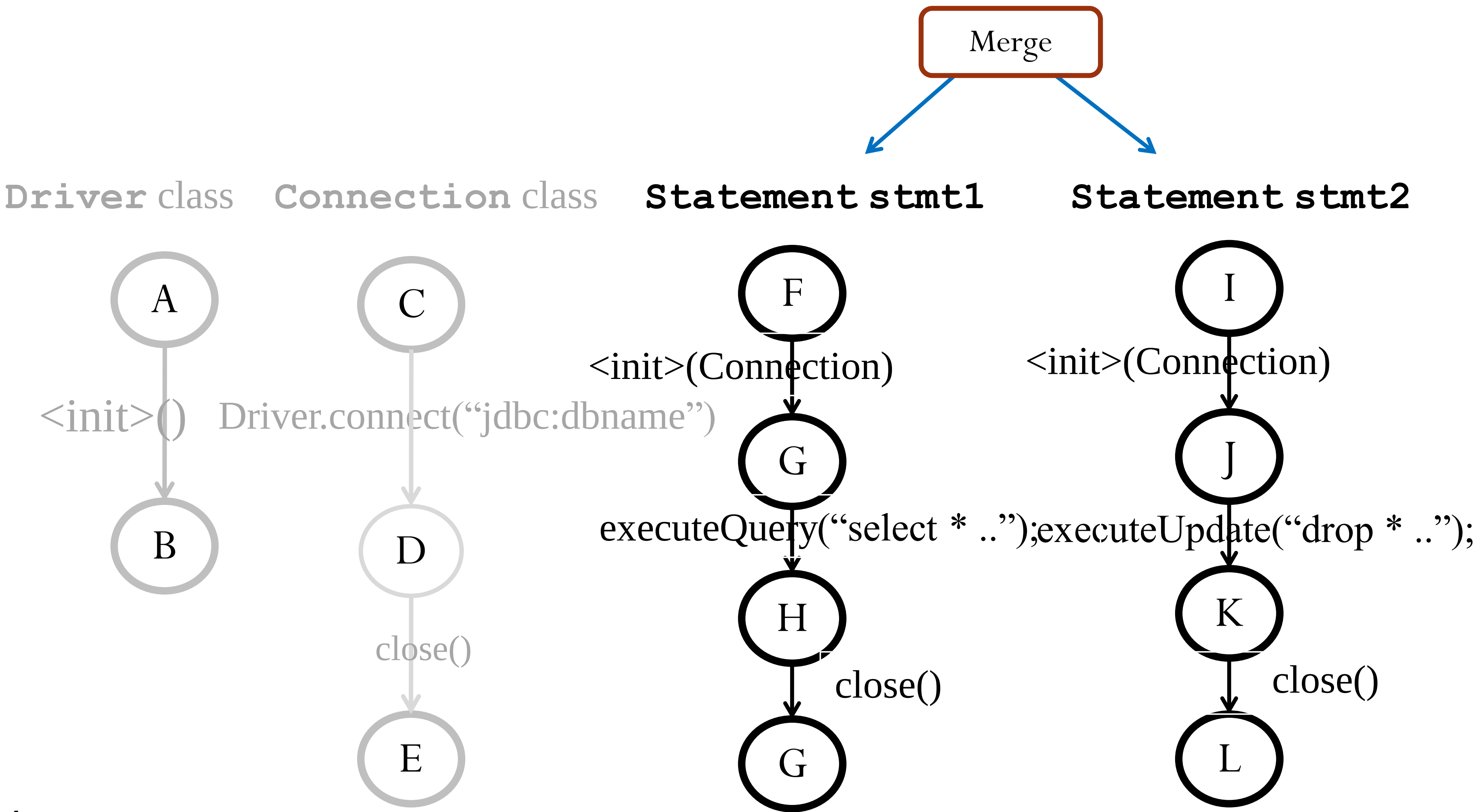
Model Inference for class `Statement`

```
Statement stmt2 =  new Statement(con);
stmt2.executeUpdate("drop table table_name");
stmt2.close();
```



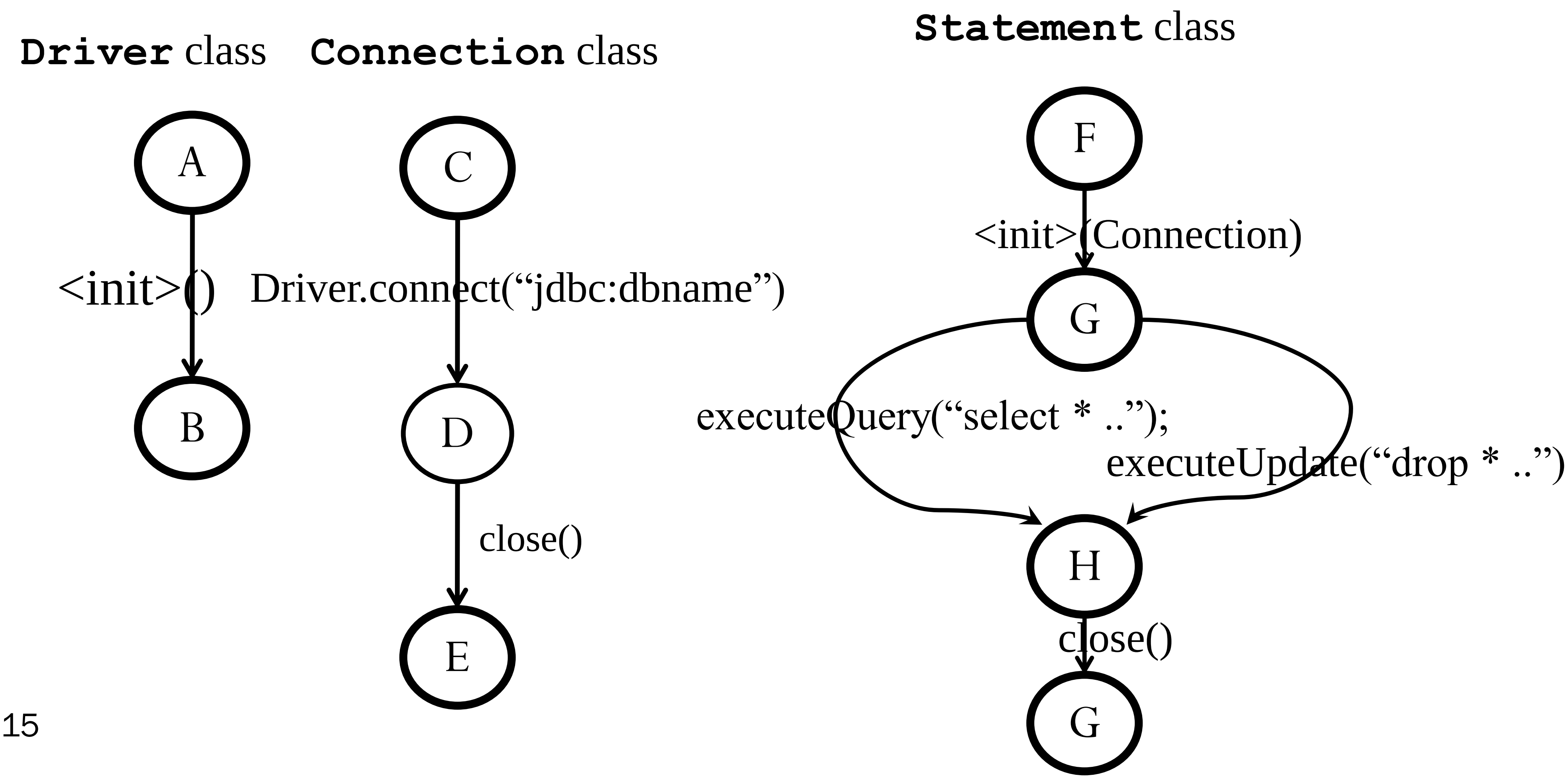
Construct a call sequence model for each **observed object**

Merge Models of the Same class

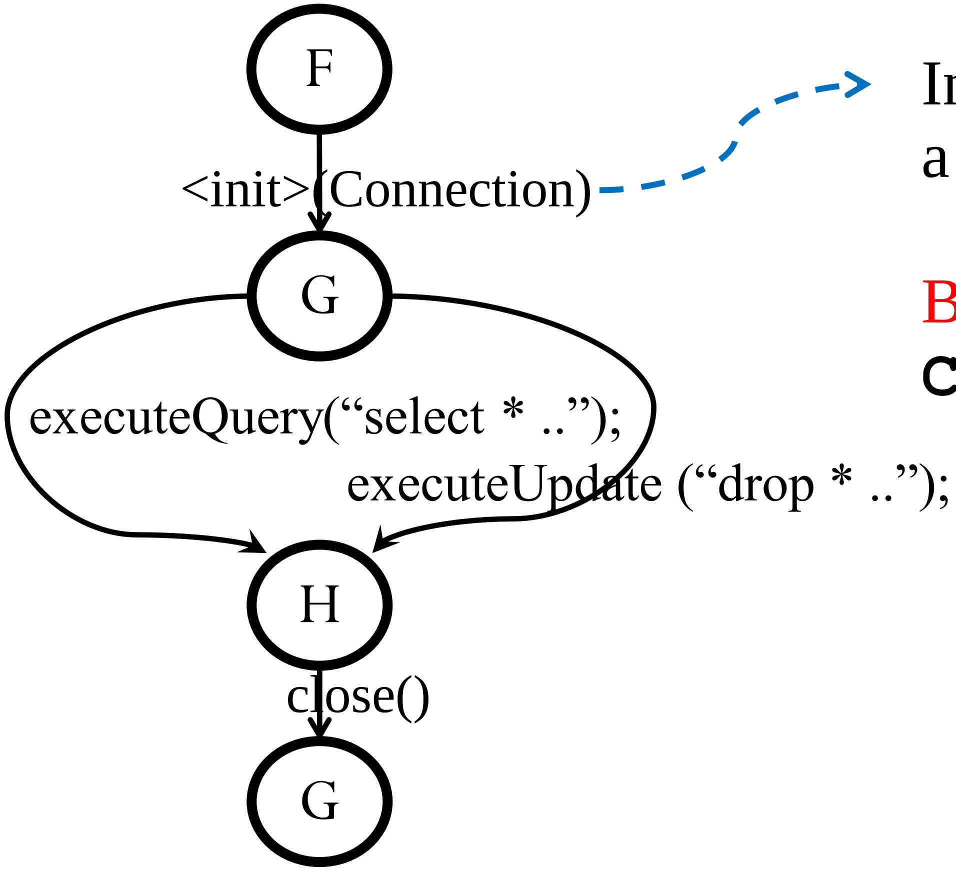


Merge models for all objects to form **one model per class**

Call Sequence Model after Merging



Enhance Call Sequence Models with Argument Constraints



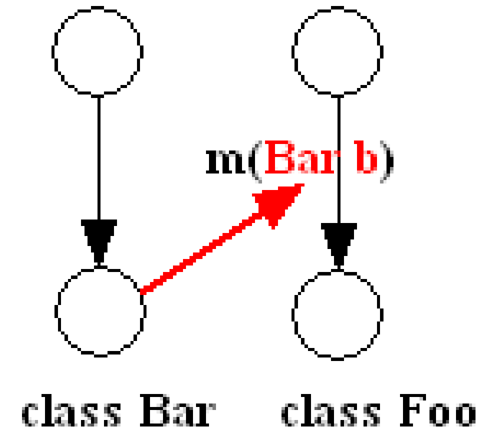
`Statement` class

Invoking the constructor requires a **`Connection`** object

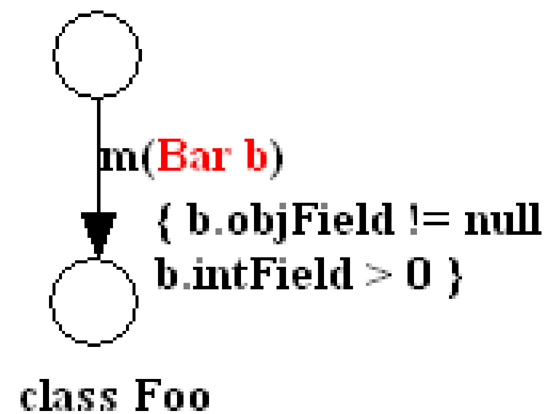
But, how to choose a desirable **`Connection`** object ?

Argument Constraints

- **Argument dependence constraint**
  - Record where the argument object values **come from**
  - Add dependence edges in the call sequence models

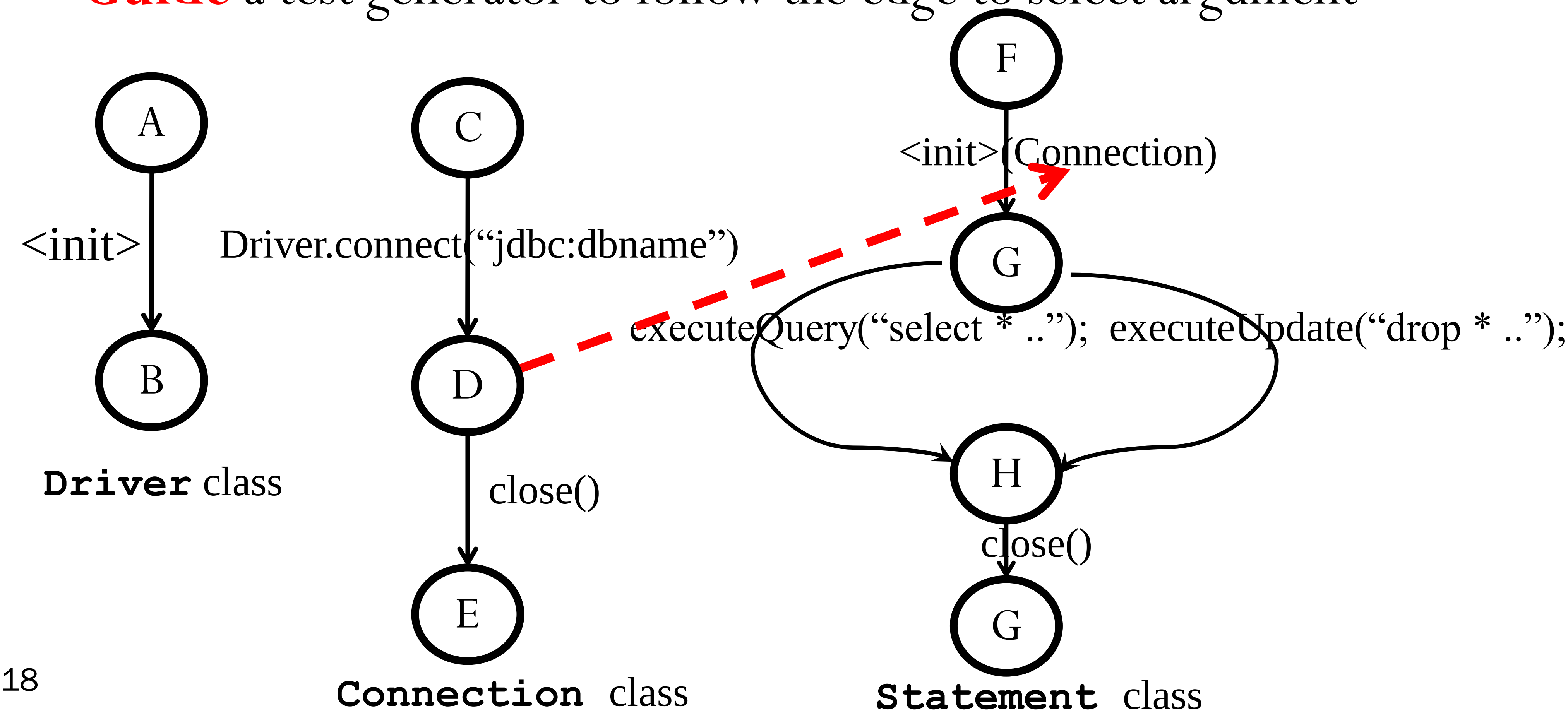


- **Abstract object profile constraint**
  - Record what the argument **value "is"**
  - Map each object field into an abstract domain as a coarse-grained measurement of "value similarity"



Argument Dependence Constraint

- Represent by a directed edge (--> below)
- **Means**: transition **F** → **G** has data dependence on node **D**, it uses the result object at the node **D**
- **Guide** a test generator to follow the edge to select argument



Abstract Object Profile Constraint

- **For each field in an observed object**
  - Map the **concrete value** → an **abstract state**

Numeric value	→	`> 0,  = 0,  < 0`
Object	→	`= null,  != null`
Array	→	`empty, null, not_empty`
Bool / enum values	→	not abstracted

- **Annotate model edges with abstract object profiles of the observed argument values from dynamic analysis**

- **Guide** test generator to choose arguments similar to what was seen at runtime

Annotate Model Edges with Abstract Object Profiles

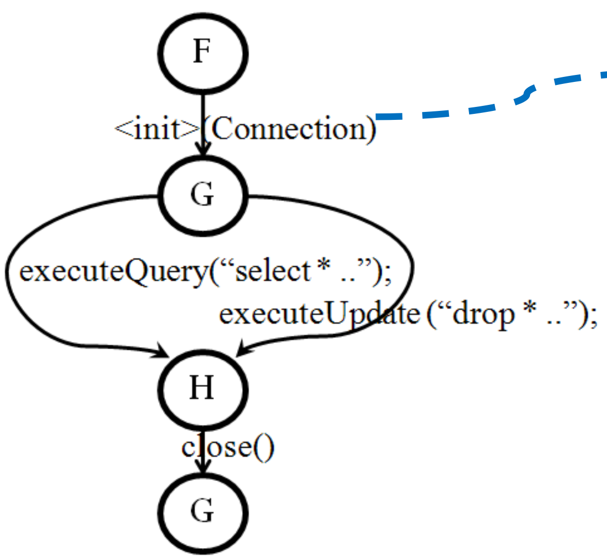
- Class **Connection** contains 3 fields

  Driver driver;   String url;   String usr;

- All observed valid **Connection** objects have a profile like:

  {driver != null, url != null, usr != null}

  - Annotate the method-call edge: **<init>(Connection)**



Statement class

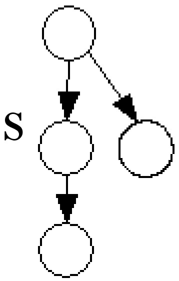
Argument **Connection**'s profile:

{driver != null, url != null, usr !=null}

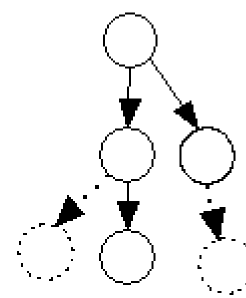
Palus prefers to pick an argument with the **same profile**, when invoking : **<init>(Connection)**

(2) Static Method Analysis

- Dynamic analysis is accurate, but **incomplete**
  - May fail to cover some methods or method invocation orders



- Palus uses static analysis to **expand** the dynamically-inferred model
  - Identify related methods, and test them together
  - Test methods not covered by the sample trace



Statically Identify Related Methods

- Two methods that access the same fields may be related (conservative)

- Two relations:
  - **Write-read**: method A reads a field that method B writes
  - **Read-read**: methods A and B reference the same field

Statically Recommends Related Methods for Testing

- Reach more program states
  - Call **`setX()`** before calling **`getX()`**

- Make the sequence more behaviorally-diverse
  - A correct execution observed by dynamic analysis will never contain:

    ```
    Statement.close();
    Statement.executeQuery("…")
    ```

  - But static analysis may suggest to call **`close()`** before **`executeQuery("…")`**

Weighting Pair-wise Method Dependence

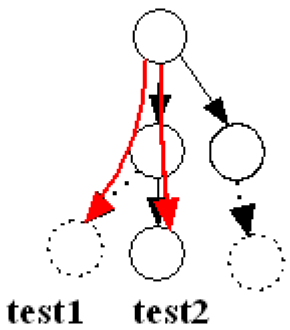
- **tf-idf weighting scheme** [Jones, 1972]
  - Palus uses it to measure the **importance** of a **field** to a **method**

$$tfidf\,(\boldsymbol{field}, \boldsymbol{method}) \propto \frac{\text{frequency of } \boldsymbol{field} \text{ in } \boldsymbol{method}}{\text{frequency of } \boldsymbol{field} \text{ in } \boldsymbol{all\ methods}}$$

- Dependence weight between two methods:

$$\boldsymbol{Weight}(\text{m1}, \text{m2}) = \sum_{\text{f} \in \text{OverlapFields(m1,m2)}} \boldsymbol{tfidf}(\mathbf{f}, \mathbf{m1})$$

(3) Model-Guided Random Test Generation: A *2-Phase* algorithm



- **Phase1**:

 Loop:

 1. Follow the **dynamically-inferred model** to select **methods** to invoke
 2. For each selected **method**
 2.1 Choose arguments using:
 - Argument dependent edge
 - Captured abstract object profiles
 - Random selection
 2.2 Use **static method dependence** information to invoke related methods

- **Phase 2:**

 Randomly generate sequences for **model-uncovered** methods
 - Use **feedback-directed** random test generation [ICSE'07]

Specify Testing Oracles in JUnit Theory

- A project-specific testing oracle in JUnit theory

```
@Theory
public void checkIterNoException(Iterator it) {
  assumeNotNull(it);
  try {
    it.hasNext();
  } catch (Exception e) {
    fail("hasNext() should never throw exception!");
  }
}
```

Palus checks that, for **every** **`Iterator`** object, calling **`hasNext()`** should **never** throw exception!

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Research Questions

- Can tests generated by Palus achieve **higher structural coverage**
- Can Palus find (more) **real-world bugs**?
- Compare with three existing approaches:

Approaches	Dynamic	Static	Random
Randoop [ICSE'07]			●
Palulu [M-TOOS'06]	●		●
RecGen [ASE' 10]		●	●
Palus (**Our approach**)	●	●	●

Subjects in Evaluating Test Coverage

- 6 open-source projects

Program	Lines of Code
tinySQL	7,672
SAT4J	9,565
JSAP	4,890
Rhino	43,584
BCEL	24,465
Apache Commons	55,400

Many Constraints (tinySQL, SAT4J, JSAP, Rhino, BCEL)

Few Constraints (Apache Commons)

Experimental Procedure

- Obtain a sample execution trace by running a simple example from user manual, or its regression test suite
- Run each tool for until test coverage becomes saturated, using the same trace
- Compare the line/branch coverage of generated tests

Test Coverage Results

Approaches	Dynamic	Static	Random	Avg Coverage
Randoop [ICSE'07]			●	39%
Palulu [M-TOOS'06]	●		●	41%
RecGen [ASE' 10]		●	●	30%
Palus (**Our approach**)	●	●	●	**53%**

- Palus **increases** test coverage
  - Dynamic analysis helps to create **legal** tests
  - Static analysis / random testing helps to create **behaviorally-diverse** tests
- Palus **falls back** to **pure random** approach for programs with few constraints (Apache Commons)

Evaluating Bug-finding Ability

- Subjects:
  - The same 6 open-source projects
  - 4 large-scale Google products
- Procedure:
  - Check 5 **default Java contracts** for all subjects
  - Write 5 **simple theories** as additional testing oracles for Apache Commons, which has partial spec

Finding Bugs in 6 open-source Projects

- Checking default Java language contracts:
  - E.g., for a non-null object o: `o.equals(o)` returns true

	Dynamic	Static	Random	Bugs
Randoop [ICSE'07]			●	80
Palulu [M-TOOS'06]	●		●	76
RecGen [ASE' 10]		●	●	42
Palus (**Our approach**)	●	●	●	**80**

  - Finds **the same number** of bugs as Randoop

- Writing additional theories as testing oracle
  - Palus finds **one new bug** in Apache Commons
    - `FilterListIterator.hasNext()` throws exception
    - **Confirmed** by Apache Commons developers

Finding Bugs in 4 Google Products

- 4 large-scale Google products

Google Product	Number of tested classes
Product A	238
Product B	600
Product C	1,269
Product D	1,455

- Each has a regression test suite with 60%+ coverage
- Go through a rigorous peer-review process

Palus Finds More Bugs

- **Palus** finds **22** real, previously-unknown **bugs**

	Dynamic	Static	Random	Bugs
Randoop [ICSE'07]			●	19
Palulu [M-TOOS'06]	●		●	18
RecGen [ASE' 10]		●	●	--
Palus (**Our approach**)	●	●	●	22

  - **3 more** than existing approaches

- Primary reasons:
  - *Fuzz* a long specific *legal* path
  - Create a ***legal*** test, ***diversify*** it, and reach program states that have not been reached before

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Related Work

- Automated Test Generation
  - **Random approaches**: **Randoop** [ICSE'07], **Palulu** [M-Toos'06], **RecGen**[ASE'10]

    Challenge in creating legal / behaviorally-diverse tests
  - **Systematic approaches**: **Korat** [ISSTA'02], Symbolic-execution-based approaches (e.g., **JPF**, **CUTE**, **DART**, **KLEE**…)

    Scalability issues; create test inputs, not object-oriented method sequences
  - **Capture-replay -based approaches**: **OCAT** [ISSTA'10], **Test Factoring** [ASE'05] and **Carving** [FSE'05]

    Save object states in memory, not create method sequences

- Software Behavior Model Inference
  - **Daikon** [ICSE'99], **ADABU** [WODA'06], **GK-Tail** [ICSE'08] …

    For program understanding, not for test generation

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Future Work

- Investigate **alternative ways** to use program analysis techniques for test generation
  - How to *better* combine static/dynamic analysis?
- What is **a good abstraction** for automated test generation tools?
  - We use an enhanced call sequence model in Palus, what about other models?
- Explain **why a test fails**
  - Automated Documentation Inference [ASE'11 to appear]
  - Semantic test simplification

Contributions

- A hybrid automated test generation **technique**
  - Dynamic analysis: infer model to create legal tests
  - Static analysis: expand dynamically-inferred model
  - Random testing: create behaviorally-diverse tests
- A publicly-available **tool**

  http://code.google.com/p/tpalus/
- An empirical **evaluation** to show its effectiveness
  - Increases test coverage
  - Finds more bugs

Backup slides

Sensitivity to the Inputs

- Investigate on two subjects: **tinySQL** and **SAT4J**

Subject	Input Size	Coverage
tinySQL	10 SQL Statements	59%
	ALL Statements from Manual	61%
SAT4J	A 5-clause formula	65%
	A 188-clause formula	66%
	A 800-clause formula	66%

- This approach is **not very sensitive** to the inputs
  - Not too many constraints in subjects?

Breakdown of Contributions in Coverage Increase