Program Testing and Analysis: Specification Mining

Dr. Michael Pradel

Software Lab, TU Darmstadt

Partly based on slides from Michael Ernst, Andreas Zeller, and Andrzej Wasylkowski

Outline

1. **Introduction**
2. **Program Invariants**
3. **Finite State Machines**
4. **Programming Rules**

Mostly based on these papers:

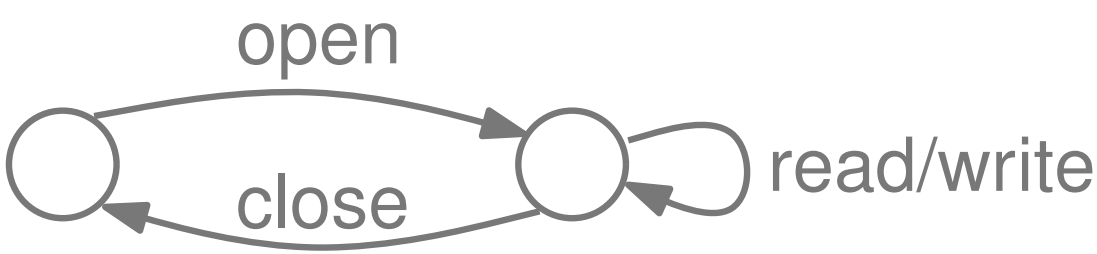
- *Dynamically Discovering Likely Program Invariants to Support Program Evolution* , Ernst et al., IEEE TSE, 2001
- *Mining Specifications*, Ammons et al., POPL, 2002
- *PR-Miner: Automatically Extracting Implicit Programming Rules and Detecting Violations in Large Software Code*, Li & Zhou, FSE 2005

Formal Specifications

- **Formal, mathematical description of the indended behavior of a program**
- **Examples:**
  - **Pre- and post-conditions:**

```
// pre: typeof(x) === "number"
function abs(x) { ... }
// post: typeof(ret) === "number" &&
//       ret >= 0
```

  - **Finite-state machines:**



Uses of Specifications

Traditionally, mainly used for formal verification

- Demonstrate that program is correct w.r.t. its specification
- Mathematical proof
- Ideally, static verification
  - Avoid running an incorrect program
- Also: Runtime verification
  - Detect and potentially prevent problems when they happen

The Problem

So why not formally specify and verify all software?

- Huge effort
- Completely specifying a large system is practically impossible
- Complex specification is likely to have mistakes
- In practice:
  - Used mostly for safetly critical systems
  - Used only to specify important properties (e.g., no crash)

Specification Mining

- Idea: Infer specifications from existing software
  - No human effort
  - Get specifications ”for free”
- Examples:
  - Pre- and post-conditions:
    Analyze function and check which properties the inputs and outputs fulfill
  - Finite state machines:
    Analyze code and identify its states and transitions between them

Wait a Minute ...

- How to validate that a program is correct by inferring the specification from the program itself?
- Sounds contradictory, but it works
  - Infer common behavior, report anomalies as potential bugs
  - Infer specifications from one code base, use them to check another
    - Different programs that use the same API
    - Different versions of the same program
  - Detect inconsistencies in the code itself (non-null assumption vs. null check)

Uses of Mined Specifications

- **Software evolution**
  - Understand behavior of program
  - Generate documentation
  - Use as oracle for regression testing
- **Anomaly detection**
  - Outliers are potential bugs
- **Support formal specification of an existing system**
  - Starting point for full specification

Outline

1. **Introduction**
2. **Program Invariants** ←
3. **Finite State Machines**
4. **Programming Rules**

Mostly based on these papers:

- *Dynamically Discovering Likely Program Invariants to Support Program Evolution* , Ernst et al., IEEE TSE, 2001
- *Mining Specifications*, Ammons et al., POPL, 2002
- *PR-Miner: Automatically Extracting Implicit Programming Rules and Detecting Violations in Large Software Code*, Li & Zhou, FSE 2005

Program Invariants

- Invariant = Data property that holds in all runs
  - At entry of f(), x is an odd number
  - $0 \leq y \leq 10$
- Useful in software development
  - Protect programmers from making erroneous changes
  - Verify properties of a program
- Can be explicitly stated in programs
  - Programmers can annotate code with invariants
  - Huge effort
  - Important invariants may be missed

Example

```
function sumArray(b, n) {
  var i = 0, s = 0;
  while (i !== n) {
    s += b[i];
    i++;
  }
  return s;
}
```

Example

Some invariants from running with 100 randomly generated inputs of length 7-13:

```
function sumArray(b, n) {
  var i = 0, s = 0;
  while (i !== n) {
    s += b[i];
    i++;
  }
  return s;
}
```

- Pre-conditions:
  - $n = b.length$
  - $7 \leq n \leq 13$
- Post-conditions:
  - $n = i = b.length$
  - $b = orig(b)$
  - $s = sum(b)$
- Loop invariants
  - $n = b.length$
  - $0 \leq i \leq 13$
  - $s = sum(b[0..i-1])$

Daikon Invariant Detector

- **Dynamic analysis: Infers invariants from particular execution**
- **Step 1: Instrument source code**
  - Trace variables of interest
- **Step 2: Run instrumented program using test suite**
- **Step 3: Infer invariants from instrumented and derived variables**

Step 1: Instrumentation

Insert instrumentation points

- Function entry
- Function exit
- Loop heads

Write to a file values for

- all variables in scope
- global variables
- function arguments
- local variables
- function's return value

Step 2: Execution

- **Instrumented program writes file with runtime values**
- **Result: Trace of execution**

Step 3: Inference

Daikon has library of invariant patterns over variables (e.g., x, y, z) and constants (e.g., a, b, c), e.g.:

- Check for each variable:
  - Constant or small number of values
- Check for numeric variables:
  - Range: $a \leq x \leq b$
- Check for multiple numbers:
  - Set of functions, e.g., $x = abs(y)$
  - Comparisons, e.g., $x < y$
- Check for sequences:
  - Sortedness

Step 3: Inference

Daikon has library of invariant patterns over variables (e.g., x, y, z) and constants (e.g., a, b, c), e.g.:

- Check for each variable:
  - Constant or small number of values
- Check for numeric variables:
  - Range: $a \leq x \leq b$
- Check for multiple numbers:
  - Set of functions, e.g., $x = abs(y)$
  - Comparisons, e.g., $x < y$
- Check for sequences:
  - Sortedness

Only matching patterns are preserved

Quiz

What post-conditions could Daikon infer from tests `g(1)` and `g(3)`?

```
function g(n) {
  var x = n * 2;
  var y = 0;
  for (var i = 0; i < x; i++) {
    y += i;
  }
  return y;
}
```

$x < y$ $\quad$ $i \geq 2$ $\quad$ $1 \leq y \leq 15$ $\quad$ $n = 1$

Quiz

What post-conditions could Daikon infer from tests `g(1)` and `g(3)`?

```
function g(n) {
  var x = n * 2;
  var y = 0;
  for (var i = 0; i < x; i++) {
    y += i;
  }
  return y;
}
```

$x < y$

$i \geq 2 \qquad 1 \leq y \leq 15$

$n = 1$