Learning from Executions

Dynamic analysis for program understanding and software engineering

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Outline

What is dynamic analysis?
Uses for dynamic analysis
Comparison with static analysis
Dynamic analysis techniques
Problem-solving and brainstorming
Implementing dynamic analysis: Executions
Implementing dynamic analysis: Monitoring
Implementing dynamic analysis: Data analysis/reporting
Combining static and dynamic analysis
Goals

Interaction among participants
Dynamic analysis is profitable: effective and easy
  • I didn’t know you could use dynamic analysis for that
  • I didn’t know how to do that with dynamic analysis
Generate ideas for your work
Dynamic analysis

Examples: profiling, testing

Execute program (over some inputs)
  • The compiler provides the semantics
Observe executions
  • Requires instrumentation infrastructure
Analyze the results
  • Use aggregation, inference, etc.
Must choose what to measure, and what test runs
Analysis challenge: What to measure?

Coverage or frequency
- Statements, branches, paths, procedure calls, types, method dispatch

Values computed
- Parameters, array indices

Run time, memory usage

Test oracle results
- Similarities among runs [Podgurski 99, Reps 97]

This choice determines what is reported
Analysis challenge: Choose good tests

The test suite determines the expense (in time and space)
The test suite determines the accuracy (what executions are never seen)

- Less accurate results are poor for applications that require correctness
- Many domains do not require correctness!

* What information is being collected also matters
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Combining static and dynamic analysis
What is dynamic analysis good for?

- Correctness
- Performance (optimization)
  - Profile-directed compilation: feed into a (static) compiler
  - Control optimizations: fall-through branches, hot paths (trace scheduling), specialize for common case
  - Data optimizations: lay out data structures, cache-aware algorithms, speculation
  - Dynamic re-compilation: JIT
  - Control optimizations: re-compile hot blocks/paths/procedures re-order dispatch table
  - Data optimizations:
    - Garbage collection: move objects for locality
    - Specialization, partial evaluation (possibly better constant propagation, etc.)
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Dynamic analysis for correctness

Finding bugs
- Violations of user-specified properties
- Deviations from past behavior (e.g., intrusion detection)

Testing
- Creating test suites
- Improving test suites

Enabling transformations

Program understanding
Dynamic analysis features

Can be as fast as execution (over a test suite, and allowing for data collection)
  • Example: aliasing

Precise: no abstraction or approximation
Unsound: results may not generalize to future executions
  • Describes execution environment or test suite
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Static analysis

Examples: compiler optimizations, type checkers, lint, program verifiers

Examine program text (no execution)
Build a model of program state
  • An abstraction of the run-time state

Reason over possible behaviors
  • E.g., “run” the program over the abstract state
Abstract interpretation

Typically implemented via dataflow analysis
Each program statement’s transfer function indicates how it transforms the (abstract) state
Example: What is the transfer function for

```c
    y = x++; 
```

?
Selecting an abstract domain

Abstract domain: \{ even, odd, either \}

\langle x \text{ is odd}; y \text{ is odd} \rangle
y = x++;  
\langle x \text{ is even}; y \text{ is odd} \rangle
Selecting an abstract domain

Abstract domain: \{ even, odd, either \}

\langle x \text{ is odd}; y \text{ is odd} \rangle
y = x++;  
\langle x \text{ is even}; y \text{ is odd} \rangle

Abstract domain: \{ prime, nonprime, anything \}

\langle x \text{ is prime}; y \text{ is prime} \rangle
y = x++;  
\langle x \text{ is anything}; y \text{ is prime} \rangle
Selecting an abstract domain

Abstract domain: set of numbers, one set per variable

\[ \langle x = \{ 3, 5, 7 \} ; y = \{ 9, 11, 13 \} \rangle \]
\[ y = x++; \]
\[ \langle x = \{ 4, 6, 8 \} ; y = \{ 3, 5, 7 \} \rangle \]
Selecting an abstract domain

Abstract domain: set of numbers, one set per variable
\[
\langle x = \{ 3, 5, 7 \}; \ y = \{ 9, 11, 13 \} \rangle \\
y = x++; \\
\langle x = \{ 4, 6, 8 \}; \ y = \{ 3, 5, 7 \} \rangle
\]

Abstract domain: set of environments

• environment assigns a variable to a number

\[
\langle x=3, \ y=11 \rangle, \ \langle x=5, \ y=9 \rangle, \ \langle x=7, \ y=1 \rangle \\
y = x++; \\
\langle x=4, \ y=3 \rangle, \ \langle x=6, \ y=5 \rangle, \ \langle x=8, \ y=7 \rangle
\]
Selecting an abstract domain

Abstract domain: set of numbers, one set per variable

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Abstract domain: set of environments

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\[ y = x++; \]
\[ \langle x=4, y=3\rangle, \langle x=6, y=5\rangle, \langle x=8, y=7\rangle \]

Abstract domain: symbolic expression per variable

\[ \langle x_n = f_1(a_{n-1}, \ldots, z_{n-1}); y_n = f_2(a_{n-1}, \ldots, z_{n-1})\rangle \]
\[ y = x++; \]
\[ \langle x_{n+1} = x_n + 1; y_{n+1} = x_n\rangle \]
Analysis challenge: Choose good abstractions

The abstraction determines the expense (in time and space)
The abstraction determines the accuracy (what information is lost)

- Less accurate results are poor for applications that require precision
- Cannot conclude all true properties in the grammar
Static analysis features

Slow to analyze large models of state, so use abstraction
Conservative: account for abstracted-away state
Sound: (weak) properties are guaranteed to be true
  • Some static analyses are not sound
## Comparing static and dynamic analysis

<table>
<thead>
<tr>
<th>Static analysis</th>
<th>Dynamic analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract domain</td>
<td>Concrete execution</td>
</tr>
<tr>
<td>slow if precise</td>
<td>slow if exhaustive</td>
</tr>
<tr>
<td>Conservative</td>
<td>Precise</td>
</tr>
<tr>
<td>due to abstraction</td>
<td>no approximation</td>
</tr>
<tr>
<td>Sound</td>
<td>Unsound</td>
</tr>
<tr>
<td>due to conservatism</td>
<td>does not generalize</td>
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</tbody>
</table>
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Coverage

Structural coverage: lexical structures in the source code

• statement, branch, path, other (def-use, condition, MCDC, etc.)
• measure the number of them (most interesting is 0 vs. non-zero)
• measure the time each one takes to execute (e.g., PC sampling)

Specification coverage

• Like structural coverage, but for expressions in the specification

Value coverage

Static analogs: dead code analysis; prediction of execution frequency
Type safety

No memory corruption or operations on wrong types of values

Dynamic type-checking

• Each value carries its type at run time
• When performing an operation, check the types of the argument
• The only type checking in Lisp, Perl, PHP, Python, Smalltalk, . . .
• Useful in statically typed languages
  • Java dynamically checks casts, has instanceof
  • C has unions
  • C++ has casts and RTTI (run-time type identification)
  • Checking type of data from external locations (files, remote calls)

Static analog: static type-checking

• Types are compile-time approximations to values
• Every type system prohibits some safe (correct) code
Slicing

What computations could affect a value
What lines of the program can affect the output?

```
if (a < 0)
    b = d;
else
    b = d
if (w < 0)
    x = y;
else
    x = z;
print(x);
```

Dynamic slicing: tracing run-time values
- Each value is tagged by
  - where it was computed
  - the values that computed it
- Follow the links backward to determine the full computation (reachability)

Static slicing: reachability over dependence graph
Memory checking

Goal: find array bound violations, uses of uninitialized memory
  • Want to find them as soon as they happen

Purify [Hastings 92]: run-time instrumentation
  • Tagged memory: 2 bits (allocated, initialized) per byte
  • Each instruction checks/updates the tags
    • Allocate (malloc): set “A” bit, clear “I” bit
    • Write (x = ...): require “A” bit, set “I” bit
    • Read (... = x): require “I” bit
    • Deallocate (free): clear “A” bit

Static analog: LCLint [Evans 96] compile-time dataflow analysis
  • Abstract state contains allocated and initialized bits
  • Each transfer function checks/updates the state
Race detection

Data race: two threads simultaneously update a data structure

• Solution: locking ensures only one thread at a time has access

Eraser [Savage 1997]: check that all shared memory accesses follow a consistent locking discipline

• Each memory location is tagged with a state:
  • virgin
  • exclusive
  • shared
  • shared-modified (indicates a race condition)

Atomicity checking: uses identical analyses statically and dynamically [Flanagan 2003]
Alias analysis

To determine whether two pointers are the same; compare the addresses
Static analog: abstract representation of the heap
Specification checking

Verify that code satisfies its specification

Dynamic analysis: assert statement

- Language is familiar to the programmer, easy to write in
- May need to remember previous values to confirm updates (pre-conditions vs. post-conditions)

Static analysis: formal verification

- theorem-proving, either manually or with machine assistance
- an open research problem
Specification generation

```java
public class StackAr {
    Object[] theArray;
    int topOfStack;
    ...
}
```

Object properties

- `theArray != null`
- `theArray.getClass() == java.lang.Object[].class`
- `topOfStack >= -1`
- `topOfStack <= theArray.length - 1`
- `theArray[0..topOfStack] elements != null`
- `theArray[topOfStack+1..] elements == null`

Pre-conditions for the StackAr constructor

- `capacity >= 0`
Specification generation II

Post-conditions for the StackAr constructor

\[
\text{orig(capacity) == theArray.length} \\
\text{theArray[]} \text{ elements == null} \\
\text{top0fStack == -1} \\
\text{theArray[0..top0fStack] == []}
\]

Post-conditions for the isFull method

\[
\text{theArray == orig(theArray)} \\
\text{theArray[]} == \text{orig(theArray[])} \\
\text{top0fStack == orig(top0fStack)} \\
\text{(return == false) } <==> \text{ (top0fStack < theArray.length - 1)} \\
\text{(return == true) } <==> \text{ (top0fStack == theArray.length - 1)}
\]
Specification generation

Dynamic invariant detection [Ernst 99]

- Machine learning over values the program computes
  - Generate-and-test strategy
  - Statistical tests to combat overfitting
- Daikon implementation is publicly available: http://pag.csail.mit.edu/daikon/
- Many applications:
  - Verifying safety properties [Vaziri 1998, Nimmer 2002]
  - Automating theorem-proving [Ne Win 2003]
  - Identifying refactoring opportunities [Kataoka 2001]
  - Predicate abstraction [Dodoo 2002]
  - Generating test cases [Xie 2003, Gupta 2003, Pacheco 2005]
  - Selecting and prioritizing test cases [Harder 2003]
  - Explaining test failures [Groce 2003]
  - Predicting incompatibilities in component upgrades [McCamant 2003]
  - Error isolation [Xie 2002, Liblit 2003]
  - Choosing modalities [Lin 2004]
  - ... and more

Statically: by hand or abstract interpretation [Cousot 77]
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Problem-solving and brainstorming

Interactive discussion

Goal:

• return home with ideas you can use
• return home with a to-do item

Start from

• specific problems
  • try to find solutions
• specific static analyses
  • try to find analogs
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Where to get them
  • Any old place tends to work pretty well.
How good are they in practice?
  • Surprisingly good
  • In other words: don’t worry
Evaluating test suites

The output

• tells you about the program, or
• tells you about the test suite or execution environment

Compare suite with actual usage

• i.e., compare analysis results over suite with analysis results over actual usage
• overhead can be a problem for current usage

Compare suite with augmented suite

• Do the results change?
• Our results suggest that you achieve diminishing returns very fast
Improving test suite quality

Use a bigger suite; sample if necessary
Lots of research in test generation
The dynamic analysis output itself tells you what you need to know
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Combining static and dynamic analysis
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1. Aggregation:
   Pre- or post-processing

2. Inspiring analogous analyses:
   Same problem, different domain

3. Hybrid analyses:
   Blend both approaches
1. Aggregation: Pre- or post-processing

Use output of one analysis as input to another

Dynamic then static
- Profile-directed compilation: unroll loops, inline, reorder dispatch, ...
- Verify properties observed at run time

Static then dynamic
- Reduce instrumentation requirements
  - Efficient branch/path profiling
  - Discharge obligations statically (type/array checks)
- Type checking (e.g., Java, including generics)
- Indicate suspicious code to test more thoroughly
2. Analogous analyses: Same problem, different domain

Any analysis problem can be solved in either domain

Examples:

- Type safety
- Slicing
- Memory checking
- Atomicity
- Specification checking
- Specification generation
Your analogous analyses here

Look for gaps with no analogous analyses!
Try using the same analysis
    • But be open to completely different approaches
There is still low-hanging fruit to be harvested
3. Hybrid analyses: Blending static and dynamic

Combine static and dynamic analyses

- Not mere aggregation, but a new analysis
- Disciplined trade-off between precision and soundness: find the sweet spot between them

Possible starting points

Analyses that trade off run-time and precision

- Different abstractions (at different program points) Switch between static and dynamic at analysis time

Ignore some available information

- Examine only some paths [Evans 94, Detlefs 98, Bush 00]

Merge based on observation that both examine only a subset of executions

- Problem: optimistic vs. pessimistic treatment

More examples: (bounded) model checking, security analyses, delta debugging [Zeller 99], etc.