

Daikon:

Dynamic Analysis for Inferring Likely Invariants

Reading: ***Dynamically Discovering Likely Program Invariants to Support Program Evolution***

15-819M: Program Analysis

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The Challenge

- Invariants are useful, but a pain to write down
- What if analysis could do it for us?
 - Problem: guessing invariants with static analysis is hard
 - Solution: guessing invariants by watching actual program behavior is easy!
 - But of course the guesses might be wrong...



Inferring $i \leq n$ in Loop Invariant

```
void sum(int *b,int n) {  
    pre:  $n \geq 0$   
    i, s := 0, 0;  
    inv:  $0 \leq i \leq n \wedge s = \sum_{0 \leq j < i} b[j]$   
    do i  $\neq$  n  $\rightarrow$   
        i, s := i+1, s+b[i]  
    post:  $s = \text{sum}(b[j], 0 \leq j < n)$   
}
```

- Possible relationships:

$i < n$ $i \leq n$ $i = n$ $i > n$ $i \geq n$

- Cull relationships with traces

Trace: $n=0$

n i

Inferring $i \leq n$ in Loop Invariant



```
void sum(int *b,int n) {  
    pre:  $n \geq 0$   
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- Possible relationships:

~~$i < n$~~ $i \leq n$ $i = n$ ~~$i > n$~~ $i \geq n$

- Cull relationships with traces

Trace: $n=0$

n	i
<hr/>	
0	0

Inferring $i \leq n$ in Loop Invariant



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void sum(int *b,int n) {  
    pre:  $n \geq 0$   
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}
```

- Possible relationships:

~~$i \leq n$~~ $i \leq n$ ~~$i \leq n$~~ ~~$i \leq n$~~ ~~$i \leq n$~~

- Cull relationships with traces

Trace: $n=1$

<u>n</u>	<u>i</u>
1	0
1	1

Inferring $i \leq n$ in Loop Invariant



```
void sum(int *b,int n) {  
    pre:  $n \geq 0$   
    i, s := 0, 0;  
    inv:  $0 \leq i \leq n \wedge s = \sum_{0 \leq j < i} b[j]$   
    do i  $\neq$  n  $\rightarrow$   
        i, s := i+1, s+b[i]  
    post:  $s = \text{sum}(b[j], 0 \leq j < n)$   
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```

- Possible relationships:

~~$i \leq n$~~ $i \leq n$ ~~$i \leq n$~~ ~~$i \leq n$~~ ~~$i \leq n$~~

- Cull relationships with traces

Trace: $n=2$

<u>n</u>	<u>i</u>
2	0
2	1
2	2



Results

- Inferred all invariants in Gries' *The Science of Programming*
- Shocking to research community
 - Many people have applied static analysis to the problem
 - Static analysis is unsuccessful by comparison



Invariants Daikon can Infer

- $x=c, x=a \parallel x=b \parallel x=c$
- $a \leq x \leq b$
- $x = a \pmod{b}, x \neq a \pmod{b}$
- $x = a*y + b*z + c$
- $x = \text{abs}(y), x = \text{min}(y,z)$
- $x = y, x < y, x \geq y$
- Invariants involving $x+y$ or $x-y$
- Sequences
 - Sorted, invariants over elements, membership, subsequence
- Derived variables
 - first/last element, or sum/min/max of array
 - element at an array index $a[i]$; $a[0..i]$ and $a[i..n]$
- x,y,z are variables; a,b,c are constants
- All are easy to falsify with test cases



Drawbacks

- Requires a reasonable test suite
- Invariants may not be true
 - May only be true for this test suite, but falsified by another program execution
- May detect uninteresting invariants
 - Some may actually tell you about the test suite, not the program (still useful)
- May miss some invariants
 - Detects all invariants in a class, but not all interesting invariants are in that class
 - Only reports invariants that are statistically unlikely to be coincidental
- ***Note: easier to reject false or uninteresting invariants than to guess true ones!***

Invariants in SW Evolution



```
void stclose(pat, j, lastj)
char  *pat;
int    *j;
int    lastj;
{
    int jt;
    int jp;
    bool      junk;

    for (jp = *j - 1; jp >= lastj ; jp--)
    {
        jt = jp + CLOSIZE;
        junk = addstr(pat[jp], pat, &jt, MAXPAT);
    }
    *j = *j + CLOSIZE;
    pat[lastj] = CLOSURE;
}
```

- Guess: loop adds chars to pat on all executions of stclose
- Inferred invariant
 - $lastj \leq *j$
 - Thus $jp = *j - 1$ could be less than lastj and the loop may not execute!
- Queried for examples where $lastj = *j$
 - When $*j > 100$
 - pat holds only 100 elements—this is an array bounds error

Invariants in SW Evolution



```
void stclose(pat, j, lastj)
char  *pat;
int   *j;
int   lastj;
{
    int jt;
    int jp;
    bool junk;

    for (jp = *j - 1; jp >= lastj ; jp--)
    {
        jt = jp + CLOSIZE;
        junk = addstr(pat[jp], pat, &jt, MAXPAT);
    }
    *j = *j + CLOSIZE;
    pat[lastj] = CLOSURE;
}
```

- Task
 - Add + operator to regular expression language
- Goal
 - Don't violate existing program invariants
- Check
 - Inferred invariants for + code same as for * code
 - Except for invariants reflecting different semantics



Benefits Observed

- Invariants describe properties of code that should be maintained
- Invariants contradict expectations of programmer, avoiding errors due to incorrect expectations
- Simple inferred invariants allow programmer to validate more complex ones

Costs



- Scalability
 - Instrumentation slowdown $\sim 10x$
 - unoptimized; later on-line work improves this
 - Invariant inference
 - Scales quadratically in # vars, linearly in trace size

Invariant Uses: Test Coverage



- Problem: When generating test cases, how do you know if your test suite is comprehensive enough?
- Generate test cases
- Observe whether inferred invariants change
- Stop when invariants don't change any more
- Captures *semantic coverage* instead of *code coverage*

Harder, Mellen, and Ernst. Improving test suites via operational abstraction. ICSE '03.

Invariant Uses: Test Selection



- Problem: When generating test cases, how do you know which ones might trigger a fault?
- Construct invariants based on “normal” execution
- Generate many random test cases
- Select tests that violate invariants from normal execution

Pacheco and Ernst. Eclat: Automatic generation and classification of test inputs. ECOOP '05.

Invariant Uses: Component Upgrades



- You're given a new version of a component—should you trust it in your system?
- Generate invariants characterizing component's behavior in your system
- Generate invariants for new component
 - If they don't match the invariants of old component, you may not want to use it!

McCamant and Ernst. Predicting problems caused by component upgrades. FSE '03.



Invariant Uses: Proofs of Programs

- Problem: theorem-prover tools need help guessing invariants to prove a program correct
- Solution: construct invariants with Daikon, use as lemmas in the proof
- Results [1]
 - Found 4 of 6 necessary invariants
 - But they were the easy ones ☹
- Results [2]
 - Programmers found it easier to remove incorrect invariants than to generate correct ones
 - Suggests that an unsound tool that produces many invariants may be more useful than a sound tool that produces few

[1] Win et al. *Using simulated execution in verifying distributed algorithms*. *Software Tools for Technology Transfer*, vol. 6, no. 1, July 2004, pp. 67-76.

[2] Nimmer and Ernst. *Invariant inference for static checking: An empirical evaluation*. *FSE '02*.