PennState

CSE 597: Security of Emerging Technologies

Module: Invariant-Based Program Analysis

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Getting the Specification is Hard

- Many program analysis rely on specification of safety, correctness, …
  - Specs are generally useful for testing, verification, documentation, etc.
- How to get the specification?
  - Rely on standard bodies (e.g., RFC, 3GPP)
  - Rely on users/developers
  - Rely on generic, program-independent specifications
    - E.g., no crashes; program must follow the CFG; …
  - ***Infer specifications***

Inferring Specifications via Dynamic Analysis

- The general idea
  - Instrument the program for collecting traces of states
  - Use traces for invariant generation
- **Daikon: use pure dynamic analysis for inv generation**
- More advanced systems
  - Combine with symbolic and machine-learning approaches

DYNAMICALLY DISCOVERING LIKELY INVARIANTS

Slides adapted from those by Tevfik Bultan

Dynamically Discovering Likely Invariants

- References
  - ``Dynamically discovering likely program invariants to support program evolution,'' Michael D. Ernst, Jake Cockrell, William G. Griswold, and David Notkin. IEEE Transactions on Software Engineering, vol. 27, no. 2, Feb. 2001, pp. 1-25.
  - ``Quickly detecting relevant program invariants,'' Michael D. Ernst, Adam Czeisler, William G. Griswold, and David Notkin. ICSE 2000, Proceedings of the 22nd International Conference on Software Engineering, pp. 449-458.

- There is also a tool which implements the techniques described in the above papers
  - Daikon (https://plse.cs.washington.edu/daikon/)
    - Works on C, C++, Java, Lisp
    - Extensible to other languages given instrumentation support

Dynamically Discovering Likely Invariants

- The main idea is to discover ***likely*** program ***invariants*** from a given program
- In this work, an ***invariant*** means an assertion that consistently holds true at a particular program point (not necessarily all program points)
- They discover *likely* program invariants – invariants observed from the provided traces
  - The only thing that is guaranteed is that the discovered properties hold for all the inputs in the test set
  - There is no guarantee that the discovered invariants will hold for all inputs; no guarantee of soundness
  - No guarantee of completeness either

An Example

- An example from "The Science of Programming," by Gries, 1981

Program 15.1.1

Input: array b, length n

```
// Sum array b of length n into variable s
i = 0;
s = 0;
while (i != n) {
  s = s + b[i];
  i = i+1;
}
```

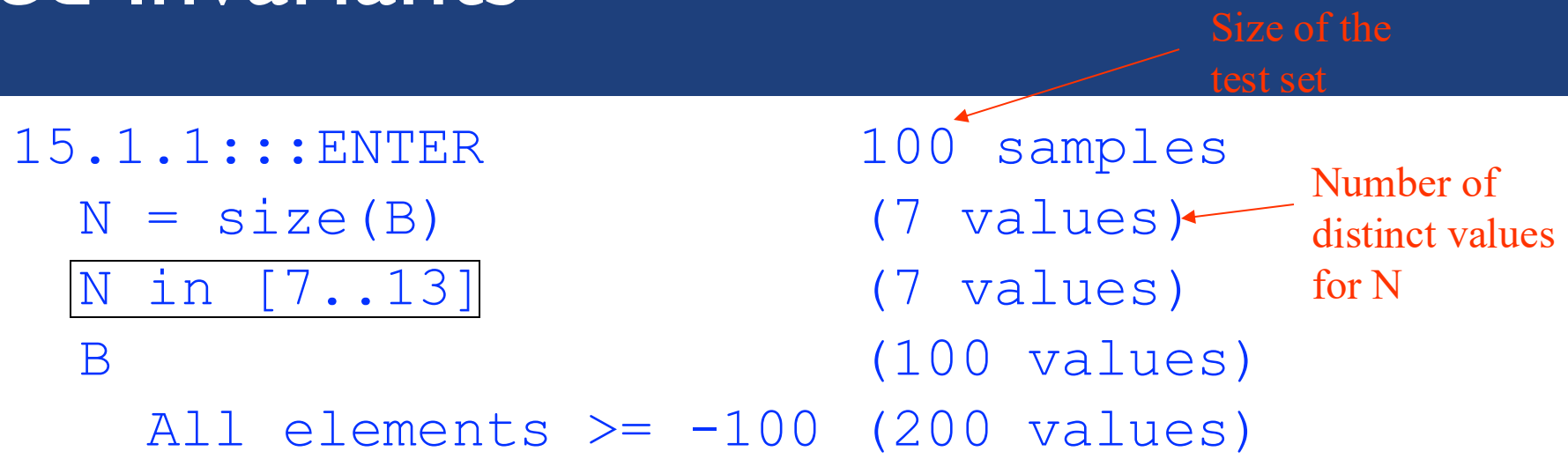
- Precondition: $n \geq 0$
- Postcondition: $s = (\Sigma\ j : 0 \leq j < n : b[j])$
- Loop invariant: $0 \leq i \leq n$ and $s = (\Sigma\ j : 0 \leq j < i : b[j])$

An Example

- One possible test set:
  - 100 randomly-generated arrays
  - Length is uniformly distributed from 7 to 13
  - Elements are uniformly distributed from –100 to 100

- Daikon discovers invariants by
  - running the program on this test set
  - monitoring the values of the variables

Discovered Invariants



- These are the assertions that hold at the entry to the procedure
  - likely preconditions

- The invariant in the box implies the precondition of the original program (it is a stronger condition that implies the precondition that `N` is non-negative)

Discovered Invariants

```
15.1.1:::EXIT                100 samples
  N = I = orig(N) = size(B) (7 values)
  B = orig(B)               (100 values)
  S = sum(B)                (96 values)
  N in [7..13]                  (7 values)
  B                         (100 values)
    All elements >= -100    (200 values)
```

- These are the assertions that hold at the procedure exit
  - likely postconditions

- Note that orig(B) corresponds to Old.B in contracts

Discovered Invariants

```
15.1.1:::LOOP                                  1107 samples
  N = size(B)                                  (7 vallues)
  S = sum(B[0..I-1])                           (452 values)
  N in [7..13]                                 (7 values)
  I in [0..13]                                 (14 values)
  I <= N                                       (77 values)
  B                                            (100 values)
    All elements in [-100..100]                (200 values)
  sum(B) in [-556..539]                        (96 values)
  B[0] nonzero in [-99..96]                    (79 values)
  B[-1] in [-88..99]                           (80 values)
  B[0..I-1]                                    (985 values)
   All elements in [-100..100]                 (200 values)
  N != B[-1]                                   (99 values)
  B[0] != B[-1]                                (100 values)
```

Means last element

- These are the assertions that hold at the loop entry and exit
  - likely loop invariants

A Different Test Set

- Instead of using a uniform distribution for the length and the contents of the array, an exponential distribution is used

- The expected values for the array lengths and the element values are same for both test sets

Discovered Invariants

```
15.1.1:::ENTER                100 samples
  N = size(B)                 (24 values)
  N >= 0                      (24 values)
```

Discovered Invariants

```
15.1.1:::EXIT                    100 samples
  N = I = orig(N) = size(B)    (24 vallues)
  B = orig(B)                  (96 values)
  S = sum(B)                   (95 values)
  N >= 0                    (24 values)
```

Discovered Invariants

```
15.1.1:::LOOP                                  1107 samples
  N = size(B)                                  (24 vallues)
  S = sum(B[0..I-1])                           (858 values)
  N in [0..35]                                 (24 values)
  I >= 0                                       (36 values)
  I <= N                                (363 values)
  B                                     (96 values)
    All elements in [-6005..7680]  (784 values)
  sum(B) in [-15006..21244]                    (95 values)
  B[0..I-1]                                    (887 values)
   All elements in [-6005..7680]   (784 values)
```

An Example

- Going back to the example

Input: array b, length n

```
// Sum array b of length n into variable s
i = 0;
s = 0;
while (i != n) {
   s = s + b[i];
   i = i+1;
}
```

With insufficient traces, we may get other invariants that are not always true:

- s >= 0
- n < 20

- Precondition: $n \geq 0$
- Postcondition: $s = (\Sigma\ j : 0 \leq j < n : b[j])$
- Loop invariant: $0 \leq i \leq n$ and $s = (\Sigma\ j : 0 \leq j < i : b[j])$

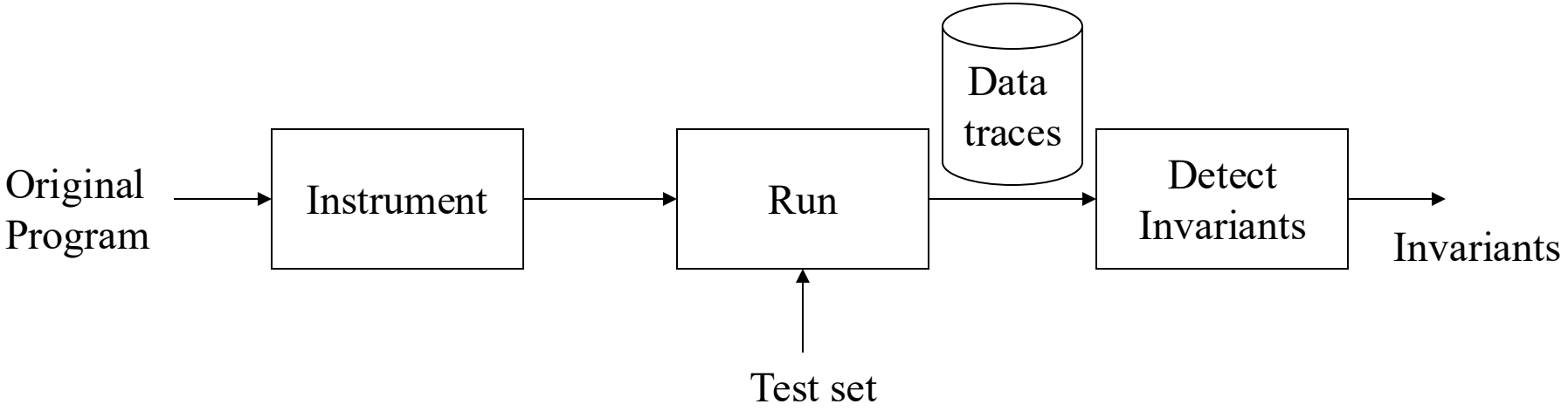
Can these be broken?

Dynamic Invariant Detection

- How does dynamic invariant generation work?

1. Run the program on a test set
2. Monitor the program execution
3. Look for potential properties that hold for all the executions

Dynamic Invariant Detection



- Instrument the program to write data trace files
- Run the program on a test set
- Offline invariant engine reads data trace files, checks for a collection of potential invariants

Inferring Invariants

- There are several issues
  1. Choosing where to infer
  2. Which invariants to infer
  3. Inferring the invariants

- Daikon infers invariants at specific program points
  - procedure entries
  - procedure exits
  - loop heads (optional)

- Daikon can only infer certain types of invariants
  - it has a library of invariant patterns (value constraints, binary/ternary relations)
  - it can only infer invariants which match to these patterns
  - These patterns can be extended by users

Trace Values

- Daikon supports two forms of data values
  - Scalar
    - number, character, boolean
  - Sequence of scalars
- All trace values must be converted to one of

```
type DataRecord struct {
    Identifier int
    Label      string
    Info struct {
        Detail1 string
        Detail2 int
    }
    Tags []string
    InfoPointer *Info
}
```

- For example, an array A of tree nodes each with left and a right child would be converted into two arrays
  - A.left (containing the object IDs for the left children)
  - A.right

Invariant Patterns

- Invariants over any variable x (where a, b, c are computed constants)
  - Constant value: $x = a$
  - Uninitialized: $x = \text{uninit}$
  - Small value set: $x \in \{a, b, c\}$
    - variable takes a small set of values

- Invariants over a single numeric variable:
  - Range limits: $x \geq a$, $x \leq b$, $a \leq x \leq b$
  - Nonzero: $x \neq 0$
  - Modulus: $x = a \pmod{b}$
  - Nonmodulus: $x \neq a \pmod{b}$
    - reported only if x mod b takes on every value other than a

Invariant Patterns

- Invariants over two numeric variables x, y
  - Linear relationship: $y = ax + b$
  - Ordering comparison: $x < y$, $x \leq y$, $x \geq y$, $x > y$, $x = y$, $x \neq y$
  - Functions: $y = fn(x)$ or $x = fn(y)$
    - where fn is absolute value, negation, bitwise complement
  - Invariants over x+y
    - invariants over single numeric variable where x+y is substituted for the variable
  - Invariants over x-y

Invariant Patterns

- Invariants over three numeric variables
  - Linear relationship: z = ax + by + c, y=ax+bz+c, x=ay+bz+c
  - Functions z = fn(x,y)
    - where fn is min, max, multiplication, and, or, greatest common divisor, comparison, exponentiation, floating point rounding, division, modulus, left and right shifts
    - All permutations of x, y, z are tested (three permutations for symmetric functions, 6 permutations for asymmetric functions)

Invariant Patterns

- Invariants over a single sequence variable
  - Range: minimum and maximum sequence values (based on lexicographic ordering)
  - Element ordering: nondecreasing, nonincreasing, equal
  - Invariants over all sequence elements: such as each value in an array being nonnegative

Invariant Patterns

- Invariants over two sequence variables: x, y
  - Linear relationship: $y = ax + b$, elementwise
  - Comparison: $x < y$, $x \leq y$, $x \geq y$, $x > y$, $x = y$, $x \neq y$ (based on lexicographic ordering)
  - Subsequence relationship: x is a subsequence of y
  - Reversal: x is the reverse of y

- Invariants over a sequence x and a numeric variable y
  - Membership: $y \in x$

Inferring Invariants

- For each invariant pattern
  - determine the constants in the pattern
  - stop checking the invariants that are falsified

- For example,
  - For invariant pattern $x \geq a$ we have to determine the constant a
  - For invariant pattern $x = ay + bz + c$ we have to determine the constants a, b, c

Inferring Invariants

- Consider the invariant pattern: x = ay + bz + c
- Consider an example data trace for variables (x, y, z)

  (0,1,-7), (10,2,1), (10,1,3), (0, 0,-5), (3, 1, -4), (7, 1, 1), ...
- Based on the first three values for x, y, z in the trace we can figure out the constants a, b, and c

  0 = a -7b +c

  10 = 2a + b +c

  10 = a +3b + c

  If you solve these equations for a, b, c you get: a=2, b=1, c=5
- The next two tuples (0, 0,-5), (3, 1, -4) confirm the invariant
- However the last trace value (7, 1, 1) kills this invariant
  - Hence, it is not checked for the remaining trace values and it is not reported as an invariant

Inferring Invariants

- Determining the constants for invariants are not too expensive
  - For example three linearly independent data values are sufficient for figuring out the constants in the pattern $x = ay + bz + c$
  - There are at most three constants in each invariant pattern

- Once the constants for the invariants are determined, checking that an invariant holds for each data value is not expensive
  - Just evaluate the expressions in an invariant and check the invariant

Cost of Inferring Invariants

- The cost of inferring invariants increases as follows:
  - linear in the number of program points
  - linear in the number of samples or values (test set size)
  - linear in the number of invariants checked/discovered
  - quadratic in the number of variables at a program point
    - Experimentally decided; the number of binary invariants is quadratic

Invariant Confidence

- Not all unfalsified invariants should be reported
- There may be a lot of irrelevant invariants which may just reflect properties of the test set
- If a lot of spurious invariants are reported the output may become unreadable
- One way
  - Improving (increasing) the test set would reduce the number of spurious invariants

Invariant Confidence

- For each detected invariant Daikon computes the probability that such a property would appear by chance in a random input
  - If that probability is smaller than a user specified confidence parameter, then the property is reported

- Daikon assumes a distribution and performs a statistical test
  - It checks the probability that the detected invariant would appear by chance from the distribution
  - If that probability is very low, then the invariant is reported

Invariant Confidence

- As an example, consider an integer variable x which takes values between -r/2-1 and r/2
- Assume that $x \neq 0$ for all test cases
- If the values of x is uniformly distributed between -r/2-1 and r/2, then the probability that x is not 0 is $1 - 1/r$
- Given s samples the probability x is never 0 is $(1-1/r)^s$
- If this probability is less than a user defined confidence level then $x \neq 0$ is reported as an invariant

Derived Variables

- Looking for invariants only on variables declared in the program may not be sufficient to detect all interesting invariants

- Daikon adds certain derived variables (which are actually expressions) and also detects invariants on these derived variables

Derived Variables

- Derived from any sequence s:
  - Length: size(s)
  - Extremal elements: s[0], s[1], s[size(s)-1], s[size(s)-2]
    - Daikon uses s[-1] to denote s[size(s)-1] and s[-2] to denote s[size(s)-2]

- Derived from any numeric sequence s:
  - Sum: sum(s)
  - Minimum element: min(s)
  - Maximum element: max(s)

Derived Variables

- Derived from any sequence s and any numeric variable i
  - Element at the index: s[i], s[i-1]
  - Subsequences: s[0..i], s[0..i-1]

- Derived from function invocations:
  - Number of calls so far

Dynamically Detecting Invariants: Summary

- Useful reverse engineering tool
  - Redocumentation
- Can be used as a coverage criterion during testing
  - Are all the values in a range covered by the test set?
- Can be helpful in detecting bugs
  - Found bugs in an existing program in a case study
- Can be useful in maintaining invariants
  - Prevent introducing bugs; programmers are less likely to break existing invariants