Improving Software Quality using Automatic Invariant Discovery and Program Repair

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Automated program analysis techniques and tools can decrease debugging time by an average of 26% and $41 billion annually

Program Verification

Check if a program meets a given specification

Program Repair

Fix a buggy program to satisfy a given specification

Invariant Generation

```
def intdiv(x, y):
  q = 0
  r = x
  while r ≥ y:
    a = 1
    b = y
    while [??] r ≥ 2b:
      a = 2a
      b = 2b
    r = r - b
    q = q + a
    [??]
    return q
```

- Discover invariant properties at certain program locations
- Answer the question *"what does this program do ?"*

Automatic Program Repair

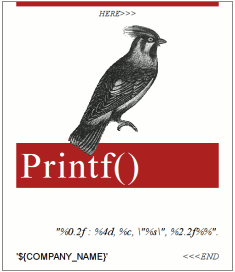
```
def intdiv(x, y):
  q = 0
  r = x
                ≠
  while r ~~≥~~ y:
    a = 1
           3*y
    b = ~~y~~
    while r ≥ 2b:
      a = 2a
      b = 2b
    r = r - b
                  −2*a
    q = q ~~+a~~

  return q
```

- Localize errors and modify code to fix bugs
- A form of *program synthesis*

Outline

- Research
  - Invariant Generation
  - Automatic Program Repair
- Current/New Research Works

How We Analyze Programs




```
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def intdiv(x, y):

    q = 0
    r = x
    while r >= y:
        a = 1
        b = y

        while r >= 2*b:
            a = 2 * a
            b = 2 * b
        r = r - b
        q = q + a

    print "x %d, y %d, q %d, r %d" %(x,y,q,r)
    return q,r

-U:---  intdiv.py        All (18,0)      (Python)--5:
```

```
x   0,  y   1,  q   0,  r  0
x   1,  y   1,  q   1,  r  0
x   1,  y   5,  q   0,  r  1
x   1,  y  10,  q   0,  r  1
x   3,  y   1,  q   3,  r  0
x   3,  y   4,  q   0,  r  3
x   3,  y   7,  q   0,  r  3
x   8,  y   1,  q   8,  r  0
x   8,  y   2,  q   4,  r  0
x   8,  y   9,  q   0,  r  8
x   8,  y  10,  q   0,  r  8
x  15,  y   1,  q  15,  r  0
x  15,  y   5,  q   3,  r  0
x  15,  y   7,  q   2,  r  1
x  20,  y   2,  q  10,  r  0
x  20,  y   7,  q   2,  r  6
x  20,  y  10,  q   2,  r  0
x 100,  y   1,  q 100,  r  0
x 100,  y   5,  q  20,  r  0
x 100,  y  10,  q  10,  r  0

-U:---  intdiv.traces   All (21,0)
```

```
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def intdiv(x, y):
    assert y != 0

    # .. compute result ..

    assert r >= 0
    assert x >= q

    return q,r

--:---  intdiv.py       All (11,0)
```
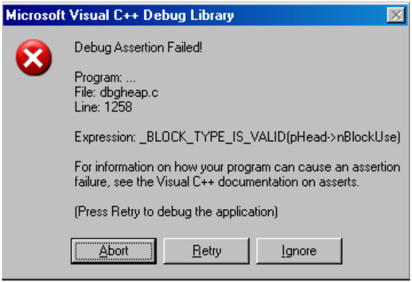

UDACITY

– Software Testing course

"GCC: 9000 assertions,
LLVM: 13,000 assertions [..]
1 assertion per 110 loc"

"program invariants are asserted properties, such as relations among variables, at certain locations in a program"



Uses

- verify programs
- help understand programs
- reveal interesting, unexpected properties
- debug (locate errors)
- documentations
- ...

Approaches to Finding Invariants

```
int intdiv(int x, int y){
  int q=0; int r=x;
  while(r ≥ y){
    int a=1; int b=y;
    while[L](r ≥ 2*b){
      a = 2*a; b = 2*b;
    }
    r=r-b; q=q+a;
  }
  return q;
}
```

x	y	q	r
0	1	0	0
1	1	1	0
3	4	0	3
8	1	8	0
15	5	3	0
20	2	10	0
100	1	100	0
	⋮	⋮	

Static Analysis

- Analyze source code directly
- Pros: guaranteed results
- Cons: computationally intensive, infer simple invariants

Dynamic Analysis

- Analyze program traces
- Pros: fast, source code not required
- Cons: results depend on traces, might not hold for all runs

Example

```
int intdiv(int x, int y){
  assert(x>0 && y>0);
  int q=0; int r=x;
  while(r ≥ y){
    int a=1;
    int b=y;
    while[L](r ≥ 2*b){
      a = 2*a;
      b = 2*b;
    }
    r=r-b;
    q=q+a;
  }
  return q;
}
```

x	y	a	b	q	r
15	2	1	2	0	15
15	2	2	4	0	15
15	2	1	2	4	7
4	1	1	1	0	4
4	1	2	2	0	4

Invariants at L: $b = ya,\ x = qy + r,\ r \geq 2ya$

DIG discovers polynomial relations of the forms

Equalities $c_0 + c_1x_1 + c_2x_n + c_3x_1x_2 + \cdots + c_mx_1^{d_1}\ldots x_n^{d_n} = 0$

Inequalities $c_0 + c_1x_1 + c_2x_n + c_3x_1x_2 + \cdots + c_mx_1^{d_1}\ldots x_n^{d_n} \geq 0, \quad c_i \in \mathbb{R}$

Examples

cubic	$z - 6n = 6,\ \frac{1}{12}z^2 - y - \frac{1}{2}z = -1$
extended gcd	$\mathrm{gcd}(a,b) = ia + jb$
sqrt	$x + \varepsilon \geq y^2 \geq x - \varepsilon$

Method

- Equalities: solve equations
- Inequalities: construct polyhedra

Example

```
int intdiv(int x, int y){
  assert(x>0 && y>0);
  int q=0; int r=x;
  while(r ≥ y){
    int a=1;
    int b=y;
    while[L](r ≥ 2*b){
      a = 2*a;
      b = 2*b;
    }
    r=r-b;
    q=q+a;
  }
  return q;
}
```

x	y	a	b	q	r
15	2	1	2	0	15
15	2	2	4	0	15
15	2	1	2	4	7
4	1	1	1	0	4
4	1	2	2	0	4

Invariants at L: $b = ya,\ x = qy + r,\ r \geq 2ya$

Finding Nonlinear Equations using Linear Equation Solving

- Terms and degrees

$$V = \{r, y, a\};\ \text{deg} = 2$$
$$\downarrow$$
$$T = \{1, r, y, a, ry, ra, ya, r^2, y^2, a^2\}$$
$$T = \{\ldots, \log(r), a^y, \sin(y), \ldots\}$$

x	y	a	b	q	r
15	**2**	**1**	2	0	**15**
15	2	2	4	0	15
15	2	1	2	4	7
4	1	1	1	0	4
4	1	2	2	0	4

- Nonlinear equation template

$$c_1 + c_2 r + c_3 y + c_4 a + c_5 ry + c_6 ra + c_7 ya + c_8 r^2 + c_9 y^2 + c_{10} a^2 = 0$$

- System of linear equations

$$\begin{aligned} \text{trace 1} \quad &: \quad \{r = 15, y = 2, a = 1\} \\ \text{eq 1} \quad &: \quad c_1 + 15c_2 + 2c_3 + c_4 + 30c_5 + 15c_6 + 2c_7 + 225c_8 + 4c_9 + c_{10} = 0 \\ &\ \vdots \end{aligned}$$

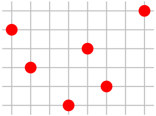
- Solve for coefficients c_i

$$V = \{x, y, a, b, q, r\};\ \text{deg} = 2 \qquad \longrightarrow \qquad b = ya, x = qy + r$$

Geometric Invariant Inference

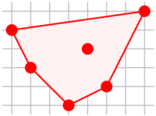
x	y
-2	1
-1	-1
1	-3
2	0
3	-2
5	2

program traces



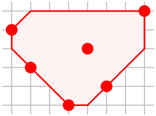
trace points

in 2D



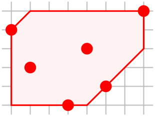
polygon

$c_1 x + c_2 y \geq c$



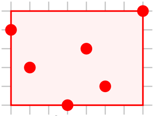
octagon

$\pm x \pm y \geq c$



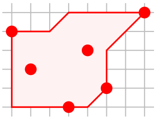
zone

$x - y \geq c$



box

$\pm x, y \geq c$

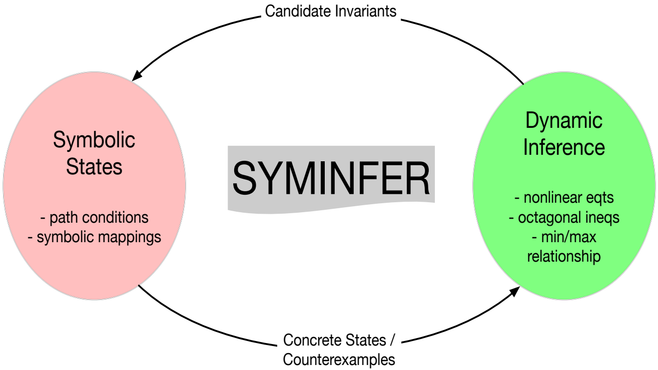


weak max-plus

(non-convex)

Symbolic States: logical formulae representing program semantics

- **path conditions** and **mappings** from variables to symbolic values
- obtained using a symbolic execution tool



- Dynamic Inference: learn *candidate* invariants under different templates from concrete states (execution traces)
- Symbolic States: check invariants and return *counterexample* states

Application: Complexity Analysis

```
void triple(int M, int N, int P){
  assert (0 <= M);
  assert (0 <= N);
  assert (0 <= P);
  int i = 0, j = 0, k = 0;
  int t = 0;
  while(i < N){
    j = 0; t++;
    while(j < M){
      j++; k = i; t++;
      while (k < P){
        k++; t++;
      }
      i = k;
    }
    i++;
  }
  [L]
}
```

Complexity of this program?

- Use t to count loop iterations
- At first glance: $t = O(MNP)$
- SymInfer found an interesting (and unexpected) nonlinear invariant at L:

$$P^2Mt + PM^2t - PMNt - M^2Nt - PMt^2 + MNt^2 + PMt - PNt - 2MNt + Pt^2 + Mt^2 + Nt^2 - t^3 - Nt + t^2 = 0$$

- Solve for t yields the most precise, unpublished bound:

$$\begin{array}{lll} t = 0 & \text{when} & N = 0, \\ t = P + M + 1 & \text{when} & N \leq P, \\ t = N - M(P - N) & \text{when} & N > P \end{array}$$

Results and Applications

Results

- ICSE'14 Distinguish Paper award
- generates correct and sufficiently strong invariants for all 28 NLA programs in SV-COMP

Applications

- *complexity* and *side-channel attacks* (**FSE'17, ASE'17, SEAD Workshop'20**)
- *AES* analysis (**ICSE'12, TOSEM'13**)
- *termination/liveness* (**OOPSLA'20**)
- *heap/pointer* (**PLDI'19**)
- *disjunctive/geometric invs* (**ICSE'14, J. Automated Reasoning'13**)
- *interactions in highly-configurable systems* (**FSE'16, ICSE'21**)

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Zune Bug

Wed morning, Dec 31, 2008: Microsoft Zune music players mysteriously froze

– Matt Akers (Microsoft Zune spokesman)

"By [Thursday] you should allow the battery to fully run out of power before the unit can restart successfully, then simply ensure that your device is recharged, then turn it back on"

Zune Bug

```
int zunebug(int days) {
  int year = 1980;
  while (days > 365) {
    if (isLeapYear(year)){
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    }
    else {
      days -= 365;
      year += 1;
    }
  }
  return year;
}
```

```
int zunebug_repair(int days) {
  int year = 1980;
  while (days > 365) {
    if (isLeapYear(year)){
      if (days > 366) {
        // days -= 366; // repair deletes
        year += 1;
      }
      days -= 366;     // repair inserts
    } else {
      days -= 365;
      year += 1;
    }
  }
  return year;
}
```

GenProg: Program Repair using Genetic Algorithm

1. Isolate faults
2. Mutate program statements and reuse existing code
3. Check repair candidates

Results

- demonstrated on bugs in real-world software (repair 16 programs over 1.25 MLocs, 2 mins avg)
- 10-year Most Influential Paper award (ICSE '19) and 10-year Most Impact Paper award (GECCO '19)

From Reachability to Synthesis

Equivalance Thm: Template-based Synthesis $\equiv$ Program Reachablity

```
def Q(i, u, d):
  if i:
    b = c0 + c1 × u + c2 × d #syn
        template
  else: b = u
  if (b > d): r = 1
  else: r = 0
  return r
```

Test suite

$$
\begin{aligned}
Q(1,0,100) &= 0\\
Q(1,11,110) &= 1\\
Q(0,100,50) &= 1\\
Q(1,-20,60) &= 1\\
Q(0,0,10) &= 0\\
Q(0,0,-10) &= 1
\end{aligned}
$$

Input: a synthesis instance

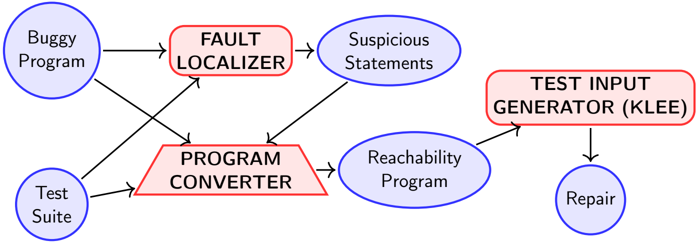
```
def pQ(i, u, d, c0, c1, c2):
  if i:
   b = c0 + c1 × u + c2 × d
  else: b = u
  if b > d: r = 1
  else: r = 0
  return r

def pmain(c0, c1, c2):
   e = pQ(1, 0,100, c0,c1,c2) == 0 and
       pQ(1,11,110, c0,c1,c2) == 1 and
       pQ(0,100,50, c0,c1,c2) == 1 and
       pQ(1,-20,60, c0,c1,c2) == 1 and
       pQ(0, 0, 10, c0,c1,c2) == 0 and
       pQ(0, 0,-10, c0,c1,c2) == 1

   if e:
     [L]  #pass the given test suite
   return 0
```

Output: a reachability instance, solvable using a test-input generation tool

CETI: Correcting Errors using Test Inputs (TACAS'17)



Non-traditional Repairs

- Corrupted *data structures* (**Google Summer of Code'18, FSE JPF Workshop'18**)
- *Fault localization* in declarative models (**ICSE '21**)
- Repair *declarative* programs (**ICSE '21**)

Outline

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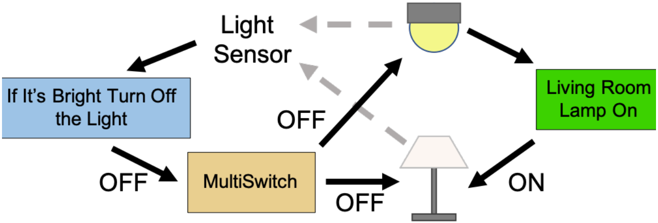
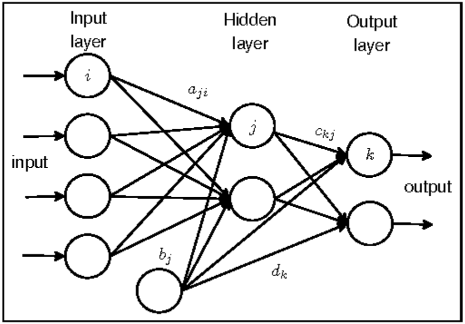
IoT Interaction Analysis and Repair (**UNL Faculty grant'21**)



Deep Neural Networks

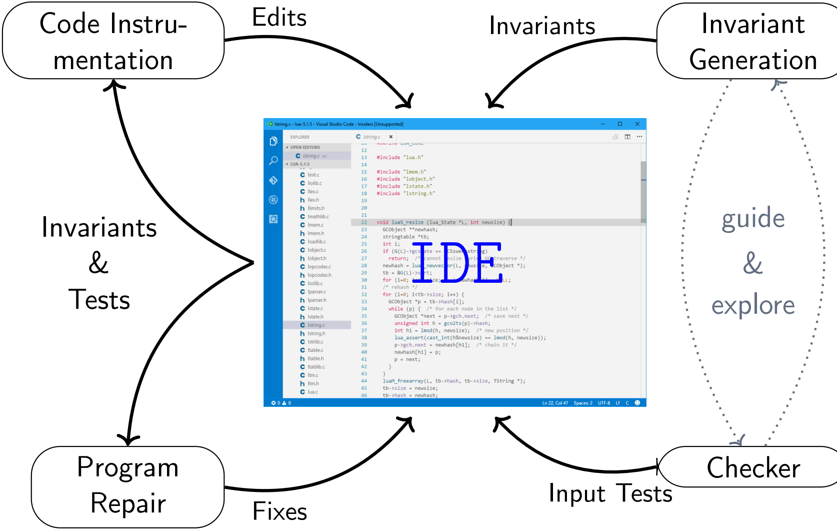


$a[1,\ldots,h][1,\ldots,n]$ ▷ Input weights
$c[1,\ldots,m][1,\ldots,h]$ ▷ Output weights
$b[1,\ldots,h]$ ▷ Hidden nodes' bias
$d[1,\ldots,m]$ ▷ Output nodes' bias

FUNCTION $\nu(\underline{x})$
  for $j \leftarrow 1$ **to** h **do**
    $r_j \leftarrow 0;$
    for $i \leftarrow 1$ **to** n **do**
      $r_j \leftarrow r_j + a_{ji} \cdot x_i + b_j$
  for $k \leftarrow 1$ **to** m **do**
    $s_k \leftarrow 0;$
    for $j \leftarrow 1$ **to** h **do**
      $s_k \leftarrow s_k + c_{kj} \cdot \sigma_h(r_j) + d_k$
    $y_k \leftarrow \sigma_o(s_k)$
  return $\underline{y}$

- Invariants (activation patterns) discovery
- Symbolic testing

IDE Integration (https://grammatech.gitlab.io/Mnemosyne/docs/muses/)



Thank you!