Model Checking and Its Applications

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Verification and Deduction Mentoring Workshop
July 13, 2018

Personal data

- Ph.d. in (non-automated) verification
- Postdoc in Model Checking (MC) with Ed Clarke at CMU
- More than 30 years of research in MC:
  same title, different contents

Current research:

- Model checking for security
- New compositional methods
- Automated program repair
- Program difference

Why Computed-Aided Verification?

It is diverse:

- Logic
- Automata
- Algorithms
- Data structures
- Very efficient implementations that matters

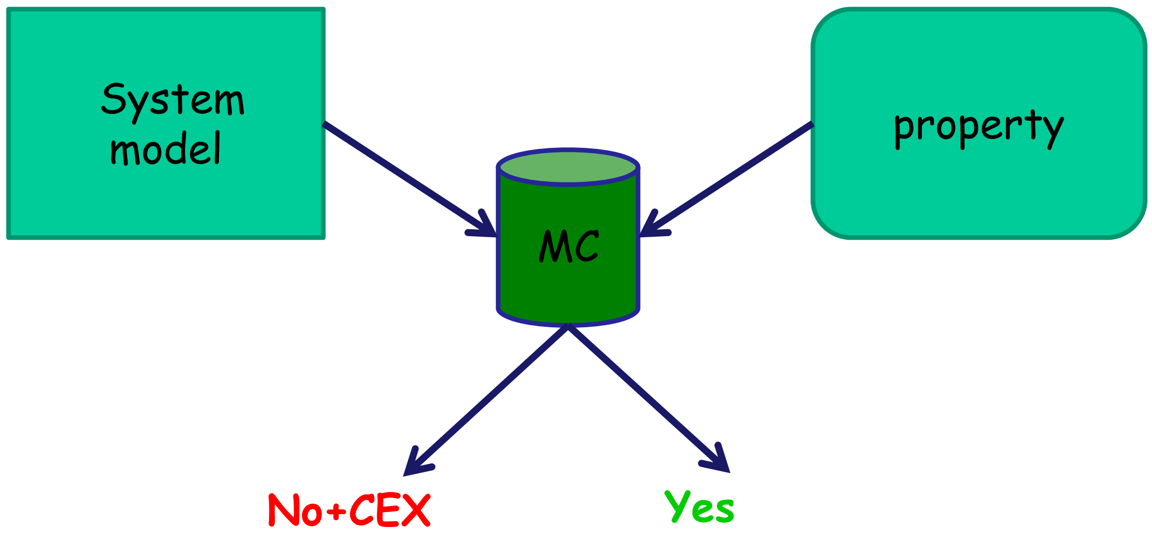
Why Computed-Aided Verification?

Research, development, applications
are done in
academia, research labs, industry

A large variety of job types

Model Checking

- Given a system and a specification, does the system satisfy the specification.



Challenges in model checking

Model checking is successfully used, but…

- Scalability
- New types of systems
- New specifications (e.g. security)
- Applications in new areas

Technologies to help

Developed or adapted by the MC community

- SAT and SMT solvers
- Static analysis
- Abstraction - refinement
- Compositional verification
- Machine learning, automata learning

And many more...

In this talk

- We show how to exploit concepts and technologies from model checking to assist in stages of program development
  - Program difference
  - Automatic program repair

Modular Demand-Driven Analysis of Semantic Difference for Program Versions

[Trostanetski, Grumberg, Kroening, SAS 2017]

PROGRAM VERSIONS

Programs change and evolve, raising the following interesting questions:

- Did the new version introduce new bugs or security vulnerabilities?
- Did the new version introduce the desired feature?
- More generally, how does the behavior of the program change?

Differences between program versions can be exploited for:

Regression testing of new version w.r.t. old version, used as "golden model"

Producing zero-day attacks on old version

characterizing changes in the program's functionality

WHAT IS A DIFFERENCE IN BEHAVIOR?

```
void p1(int& x) {
    if (x < 0)
        x = -1;
        return;
    x--;
    if (x >= 1)
        x=x+1;
        return;
    else
        while ( x ==1);
     x=0;
}
```

```
void p2(int& x) {
    if (x < 0)
        x = -1;
        return;
    x--;
    if (x > 2)
        x=x+1;
        return;
    else
        while ( x == 1);
     x=0;
}
```

FULL DIFFERENCE SUMMARY

Difference for a pair of procedures p_1, p_2 is a triplet:

– **changed:** is the set of initial states for which both procedures terminate with different final states.

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violate **Partial Equivalence**

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violate **Mutual Termination**

FULL DIFFERENCE SUMMARY

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- **unchanged:** is the set of initial states for which both procedures either terminate with the same final states, or both do not terminate.

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Full Equivalence

FULL DIFFERENCE SUMMARY

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$$\boldsymbol{changed} \cup \mathbf{termination}\_\boldsymbol{changed} \cup \boldsymbol{unchanged} = \boldsymbol{input\ space}$$

EXAMPLE

The difference summary is:

$$changed \coloneqq \{3\}$$

$$termination\_changed \coloneqq \{2\}$$

$$unchanged \coloneqq \{c : (c < 2) \lor (c > 3)\}$$

```
void p1(int& x) {
    if (x < 0)
        x = -1;
        return;
    x--;
    if (x >= 1)
        x=x+1;
        return;
    else
        while ( x ==1);
    x=0;
}
```

→

```
void p2(int& x) {
    if (x < 0)
        x = -1;
        return;
    x--;
    if (x > 2)
        x=x+1;
        return;
    else
        while ( x == 1);
    x=0;
}
```

DIFFERENCE SUMMARY - COMPUTATION

- The full difference summary is incomputable
- We compute under-approximations of changed and unchanged,

ignoring termination_changed:

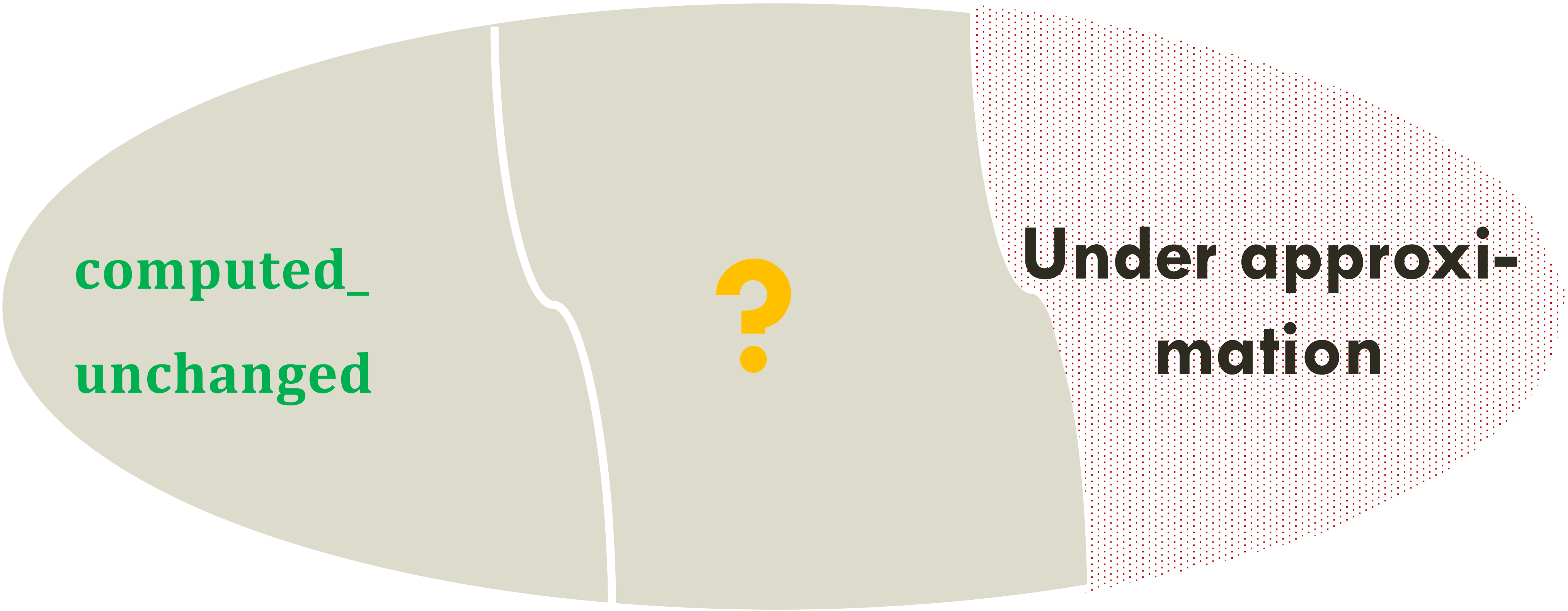
  - A set $\boldsymbol{computed\_changed} \subseteq changed$
  - A set $\boldsymbol{computed\_unchanged} \subseteq unchanged$

DIFFERENCE SUMMARY - COMPUTATION

Input space

DIFFERENCE SUMMARY - COMPUTATION

DIFFERENCE SUMMARY - COMPUTATION



DIFFERENCE SUMMARY - COMPUTATION

PROGRAM REPRESENTATION

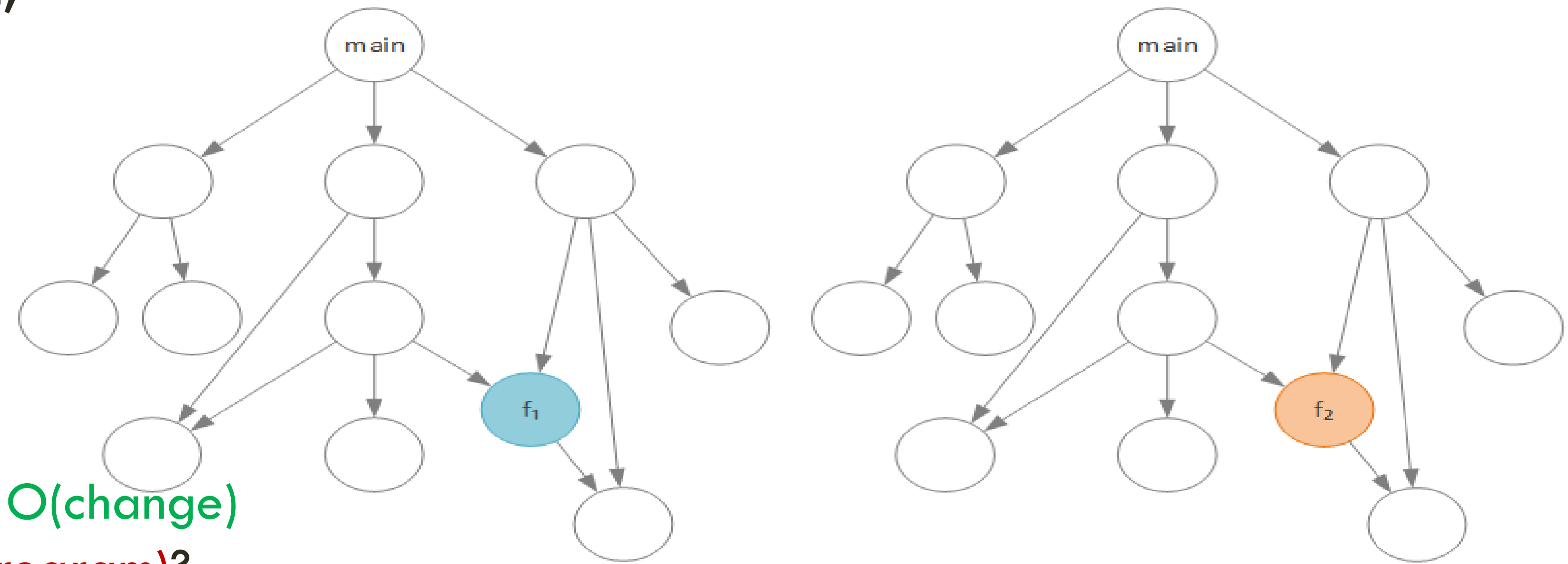
- A program is represented by a call graph
- Every procedure is represented by a Control Flow Graph (CFG)

- We are interested in the input-output behavior of the program

HOW PROGRAMS CHANGE

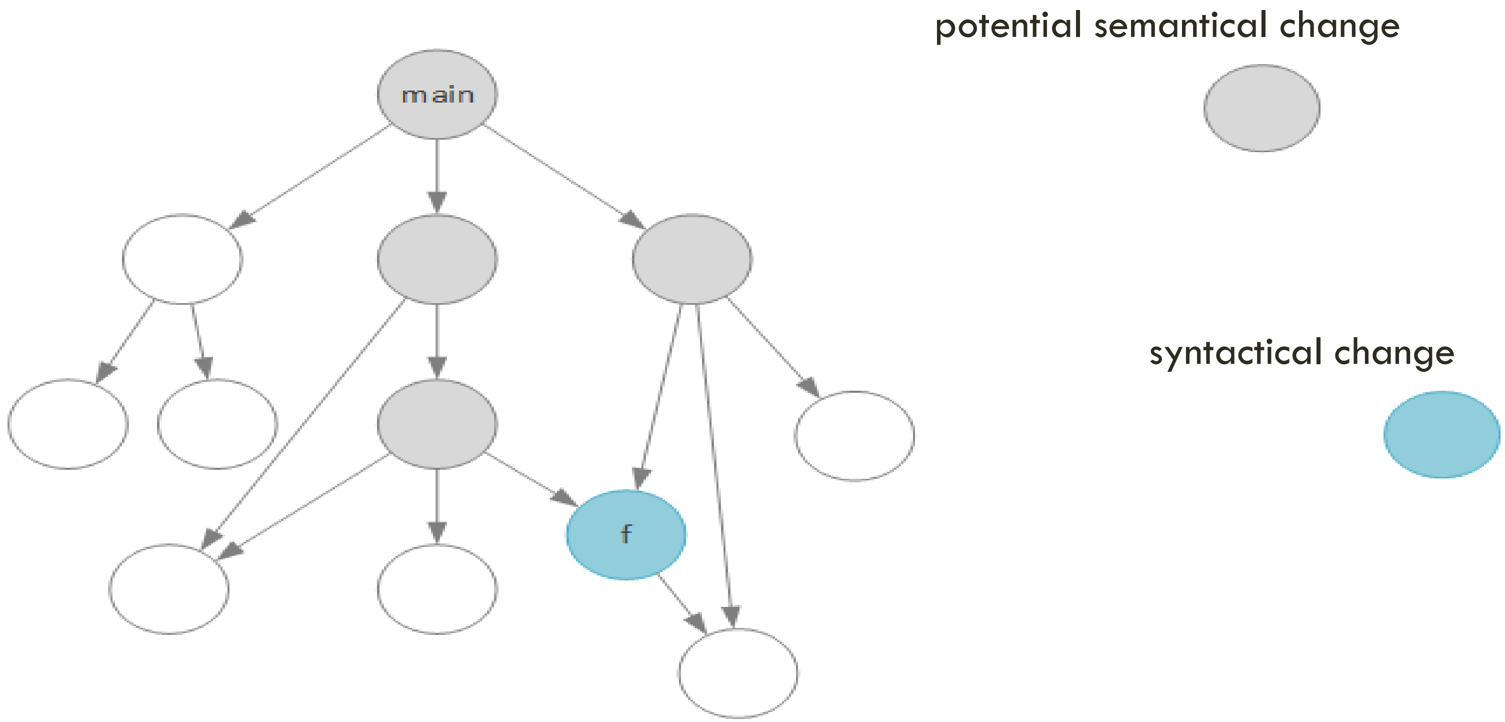
Changes are small,
programs are big

call graphs

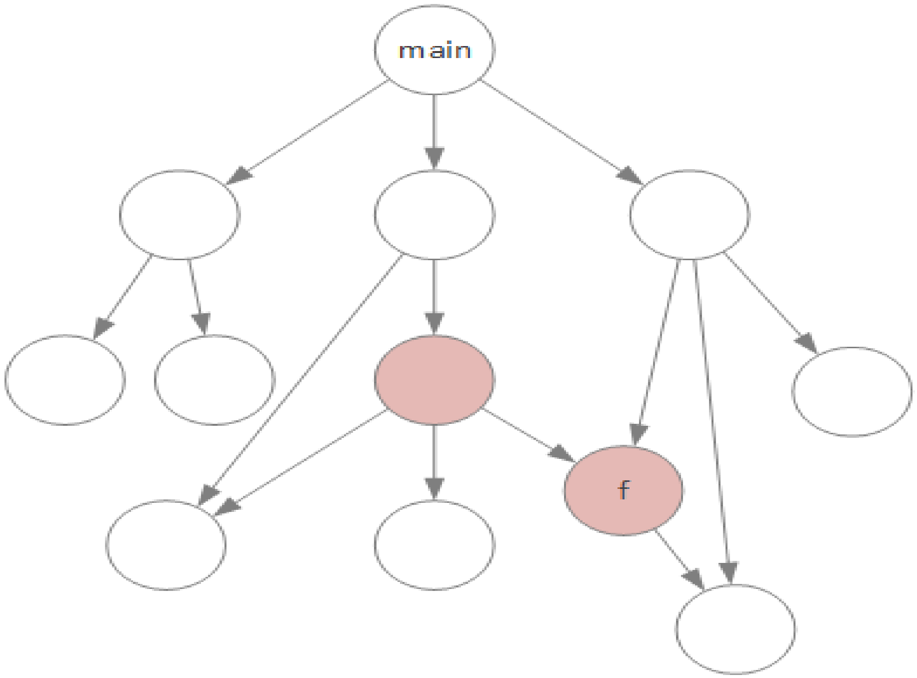


Can our work be O(change)
instead of O(program)?

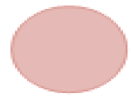
WHICH PROCEDURES COULD BE AFFECTED



WHICH PROCEDURES ARE AFFECTED



semantical change

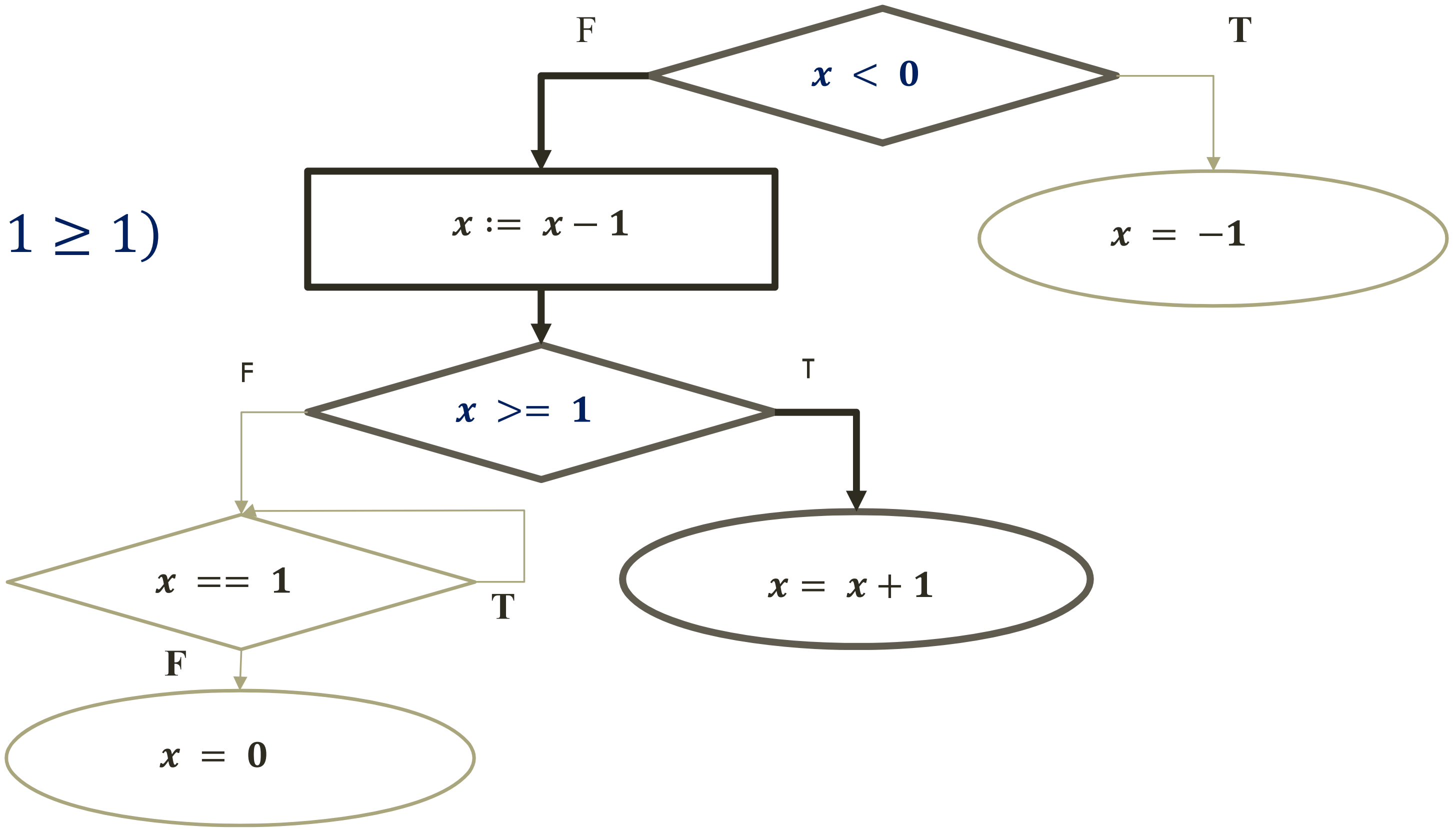


MAIN IDEAS

- Modular analysis applied to one pair of procedures at a time
  - No inlining
- Only affected procedures are analyzed
- Procedures need not be fully analyzed:
  - Unanalyzed parts are abstracted using uninterpreted functions
  - Refinement is applied upon demand
- Anytime analysis:
  - Does not necessarily terminate
  - Its partial results are meaningful
  - The longer it runs, the more precise its results are

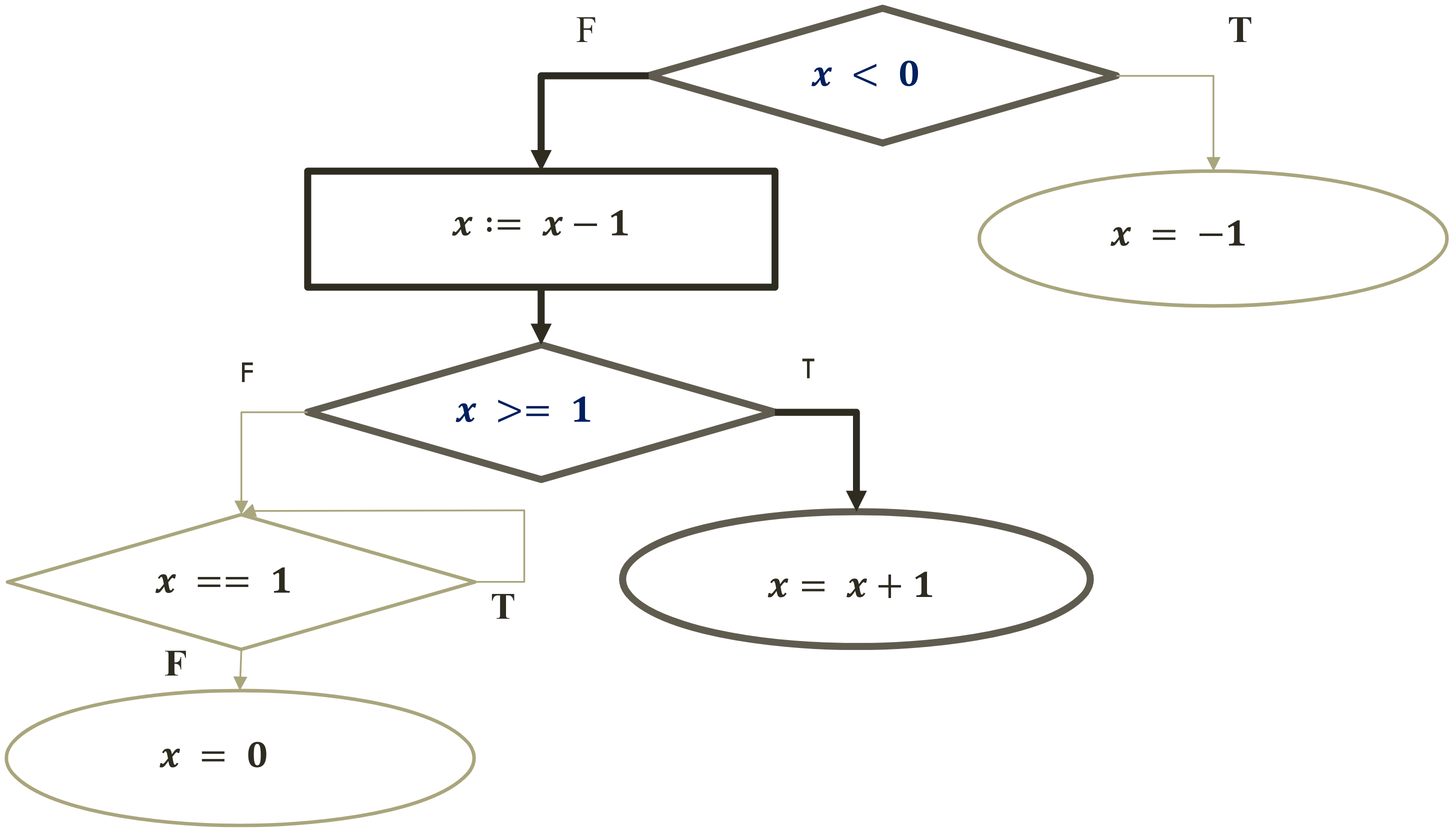
EXAMPLE

$$R_\pi(x) = x \geq 0 \land (x - 1 \geq 1)$$
$$\equiv x \geq 2$$



EXAMPLE

$$T_\pi(x) = x$$



PATH CHARACTERIZATION

For a finite path π in CFG from entry node to exit node:

- The **reachability condition** R_π is a First Order Logic Formula, which guarantees that control traverses π
- The **state transformation** T_π is an n-tuple of expressions over program variables, describing the transformation on the variables' values along π

Both given in terms of variables at the entry node of π

PROCEDURE SUMMARY

A procedure summary of procedure p is

$$Sum_p \subseteq \{ (R_\pi, T_\pi) \mid \pi \text{ is a finite path in } p\}$$

The full set of path summaries often cannot be computed, and might not be needed

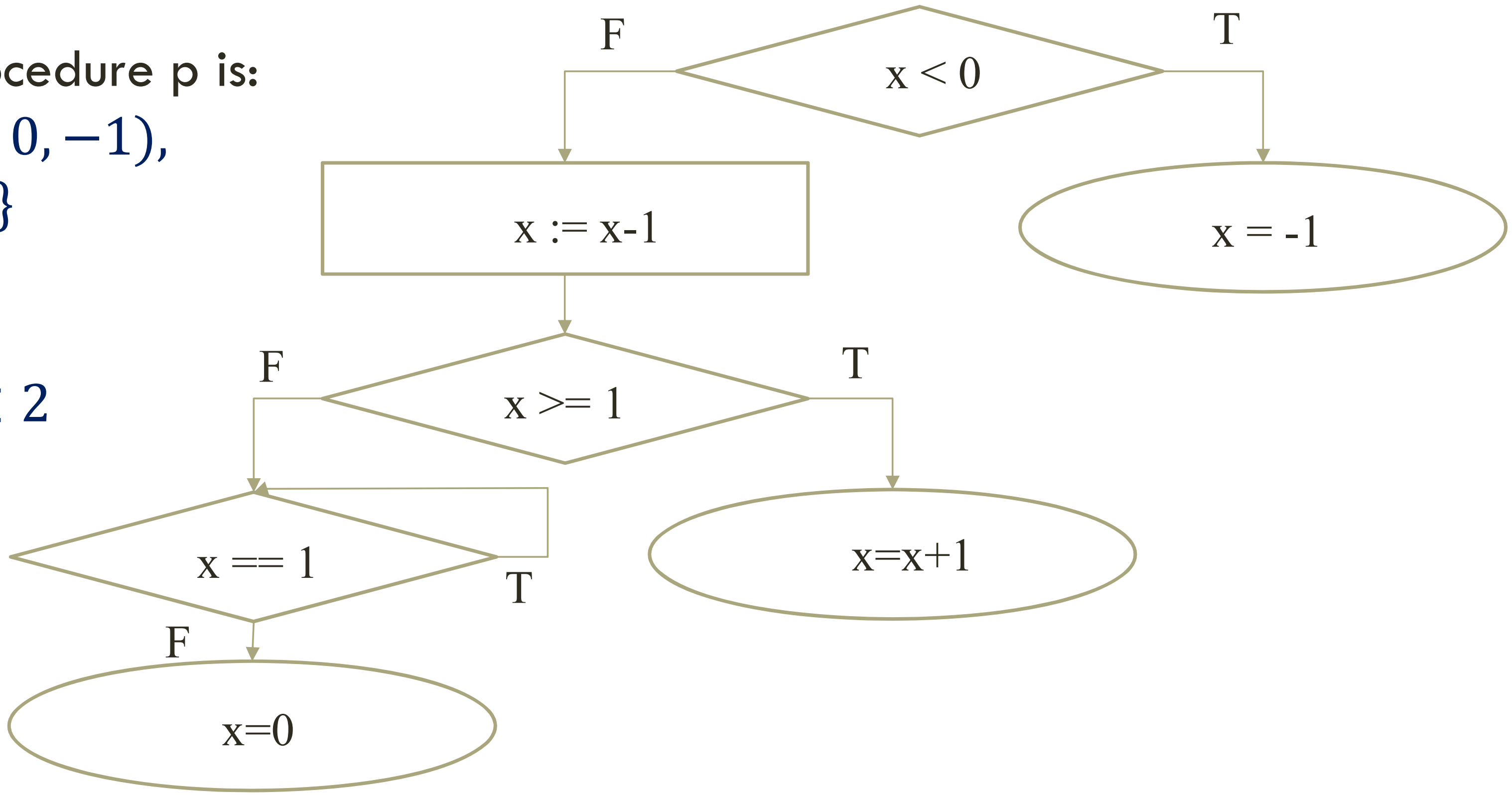
EXAMPLE

A possible summary for procedure p is:

$$sum_p = \{(x < 0, -1), (x \geq 2, x)\}$$

Its uncovered part is

$$x \geq 0 \wedge x < 2$$



FROM SUMMARY TO DIFFERENCE SUMMARY

For each (r_1, t_1) in sum_{p_1}, (r_2, t_2) in sum_{p_2}

- diffCond $:= r_1 \wedge r_2 \wedge (t_1 \neq t_2)$

If diffCond is SAT, add it to computed_changed

- eqCond $:= r_1 \wedge r_2 \wedge (t_1 = t_2)$

If eqCond is SAT, add it to computed_unchanged

SYMBOLIC EXECUTION

FOR COMPUTING (R_π, T_π)

Instruction	R	T
Assignment $x := e$	$R_\pi^{i+1} = R_\pi^i$	$\forall y \neq x \;\; T_\pi^{i+1}[y] := T_\pi^i[y]$ $T_\pi^{i+1}[x] := e[V_p \leftarrow T_\pi^i]$
Test B	$R_\pi^{i+1} = R_\pi^i \wedge \tilde{B}$	$\forall x \; T_\pi^{i+1}[x] := T_\pi^i[x]$
Procedure call $g(Y)$	Inlined	

COMPUTING THE SUMMARIES

To compute path summaries without in-lining called procedures:

We suggest modular symbolic execution

MODULAR SYMBOLIC EXECUTION

Path π of procedure p includes call g(Y) at location l_i

$sum_g = \{ (r_1, t_1), \ldots, (r_n, t_n)\}$ previously computed

Instead of in-lining g we compute:

$$R_\pi^{i+1} = R_\pi^i \wedge \bigvee_{j=1}^{n} \boldsymbol{r_j}$$

$$T_\pi^{i+1} = \boldsymbol{ITE}(\boldsymbol{r_1}, \boldsymbol{t_1}, \ldots, \boldsymbol{ITE}(\boldsymbol{r_n}, \boldsymbol{t_n}, \boldsymbol{error})..)$$

MODULAR SYMBOLIC EXECUTION

Path π of procedure p includes call g(Y) at location l_i

$sum_g = \{ (r_1, t_1), \ldots, (r_n, t_n) \}$ previously computed

Instead of in-lining g we compute:

$$R_\pi^{i+1} = R_\pi^i \wedge \bigvee_{j=1}^{n} \boldsymbol{r_j}\left[V_g \leftarrow T_\pi^i(Y)\right]$$

$$T_\pi^{i+1} = \boldsymbol{ITE}(\boldsymbol{r_1}\left[V_g \leftarrow T_\pi^i(Y)\right], \boldsymbol{t_1}\left[V_g \leftarrow T_\pi^i(Y)\right], \ldots, \boldsymbol{ITE}(\boldsymbol{r_n}\left[V_g \leftarrow T_\pi^i(Y)\right], \boldsymbol{t_n}\left[V_g \leftarrow T_\pi^i(Y)\right], \boldsymbol{error})..)$$

MODULAR SYMBOLIC EXECUTION

Path π of procedure p includes call g(Y) at location l_i

$\boldsymbol{sum_g} = \{ (\boldsymbol{r_1}, \boldsymbol{t_1}), \ldots, (\boldsymbol{r_n}, \boldsymbol{t_n})\}$ previously computed

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$$R_\pi^{i+1} = R_\pi^i \wedge \bigvee_{j=1}^{n} \boldsymbol{r_j}$$

$$T_\pi^{i+1} = \boldsymbol{ITE}(\boldsymbol{r_1}, \boldsymbol{t_1}, \ldots, \boldsymbol{ITE}(\boldsymbol{r_n}, \boldsymbol{t_n}, \boldsymbol{error})..)$$

CAN WE DO BETTER?

- Use abstraction for the un-analyzed (uncovered) parts
- Later check if these parts are needed at all for the analysis of calling procedure
- If needed - refine

ABSTRACTION

Unanalyzed parts of a procedure are replaced by uninterpreted functions

For matched procedures g_1,g_2 we have

- A common uninterpreted function UF_{g_1,g_2}
- Individual uninterpreted functions UF_{g_1} and UF_{g_2}

ABSTRACT MODULAR SYMBOLIC EXECUTION

For call $g_1(Y)$ with

$$sum_{g_1} = \{ (r_1, t_1), \dots, (r_n, t_n)\}:$$

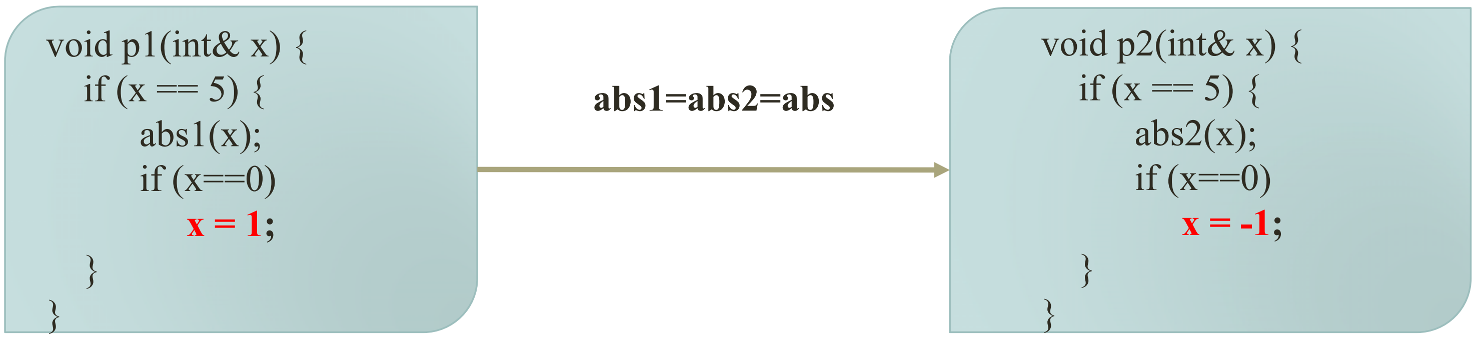
$$R_\pi^{i+1} = R_\pi^i$$

$$T_\pi^{i+1} = ITE(r_1, t_1, \dots ITE(r_n, t_n, ITE(computed\_unchanged, UF_{g_1, g_2}, UF_{g_1}))$$

For $g_2(Y)$ we use sum_{g_2} and UF_{g_2}

REFINEMENT

Since we are using uninterpreted functions, the discovered difference may not be feasible:



OVERALL ALGORITHM

- Start the analysis from the syntactically changed procedures. Analyze them with abstract modular symbolic execution up to a certain bound
- Compute difference summaries for those procedures. If you can prove equivalence for all inputs – stop.
- Use refinement when needed
- Repeat for calling procedures
- Can be guided towards interesting procedures by the user

EXPERIMENTAL RESULTS – EQUIVALENT BENCHMARKS

We compared to two tools that prove equivalence between procedures:

- Regression Verification Tool (RVT)

Godlin, Benny, and Ofer Strichman. "**Regression verification**." *Proceedings of the 46th Annual Design Automation Conference*. ACM, 2009.

- SymDiff

Lahiri, Shuvendu K., et al. "**SYMDIFF: A Language-Agnostic Semantic Diff Tool for Imperative Programs.**" *CAV*. Vol. 12. 2012.

Sound and Complete Mutation-Based Program Repair

[Rothenberg, Grumberg, FM'16]

Mutation-Based Program Repair

Sequential program

Assertions in code

Given set of mutations

Can we use these mutations to make all assertions hold?

Assignments, conditionals, loops and function calls

Assertion violation

operator replacement (+ → -), constant manipulation ($c \rightarrow c + 1$)

Return all possible repairs

Example

```
int f(int x, int y){
    int z;
    if  (x + y > 8) {
        z = x + y;
    } else {
        z = 9;
    }
    if (z ≥ 9)  z = z − 1;
    assert(z > 8);
    return z;
}
```

$x = 5, y = 2$

$z = 9$

$z = 8$

Example

```
    int f(int x, int y){
1.      int z;
2.      if (x + y > 8) {
3.              z = x + y;
4.      } else {
5.              z = 9;
6.      }
7.      if (z ≥ 9) z = z + 1;
8.      assert(z > 8);
9.      return z;
    }
```

At this point $z \geq 9$

Mutation list:

- Replace + with –
- Replace – with +
- Replace > with ≥
- Replace ≥ with >

Note: Repairs are **minimal**

Repair list:

option 1:

line 7: *replace* $\geq$ *with* $>$

option 2:

line 7: *replace* $-$ *with* $+$

Example

```
int f(int x, int y){
    int z;
    if (x + y > 9) {
        z = x + y;
    } else {
        z = 10;
    }
    if (z ≥ 9) z = z − 1;
    assert(z > 8);
    return z;
}
```

At this point z ≥ 10

Mutation list:

- Replace + with –
- Replace – with +
- Replace > with ≥
- Replace ≥ with >
- Increase constants by 1

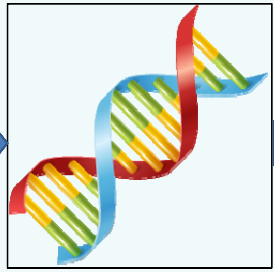
Overview of our approach

$int\ f(int\ x, int\ y)\{$
1. $int\ z;$
2. $if\ \ (x + y > 8)\ \{$
3. $z = x + y;$
4. $\}\ else\ \{$
5. $z = 9;$
6. $\}$
7. $if\ (z \geq 9)\ \ z = z - 1;$
8. $assert(z > 8);$
9. $return\ z;$

$\}$

Input:
a buggy program

Translation



Mutation

Repair

$line\ 7:\ replace\ operator\ \geq with >$
$line\ 7:\ replace\ operator\ - \ with +$
$\ldots$

Output:
All **minimal** repairs,
sorted by size

Finding all correct programs
from a finite set of programs

Finding all unsatisfiable constraint sets
from a finite set of constraint sets

First step - Translation

Goal: Translate the program into a **set of constraints** which is **satisfiable iff the program has a bug**
(i.e. there exists an input for which an assertion fails)

Work by Clarke,Kroening,Lerda (TACAS 2004)
(CBMC)

- Simplification
- Unwinding of loops
  - a **bounded** number of unwinding
- Conversion to SSA

Correctness is bounded

Translation

$int\ f(int\ x, int\ y)\{$

1. $int\ z;$
2. $if\ \ (x + y > 8)\ \{$
3. $\quad z = x + y;$
4. $\}\ else\ \{$
5. $\quad z = 9;$
6. $\}$
7. $if\ (z \geq 9)\ \{$

   $\quad z = z - 1;$

   $\}$
8. $assert(z > 8);$
9. $return\ z;$

$\}$

$g_1 = x_1 + y_1 > 8$

$z_2 = x_1 + y_1$

$z_3 = 9$

$z_4 = g_1 ? z_2 : z_3$

$b_1 = z_4 \geq 9$

$z_5 = z_4 - 1$

$z_6 = b_1 ? z_5 : z_4$

$z_6 \leq 8$

$g_1 = x_1 + y_1 > 8$

Second step - Mutation

Mutation list:
- Replace + with –
- Replace – with +
- Replace > with ≥
- Replace ≥ with >

```
   int f(int x, int y){
1.      int z;
2.      if (x + y > 8) {
3.           z = x – y;
4.      } else {
5.           z = 9;
6.      }
7.      if (z ≥ 9) {
          z = z – 1;
        }
8.      assert(z > 8);
9.      return z;
   }
```

$\{g_1 = x_1 + y_1 > 8, g_1 = x_1 - y_1 > 8, g_1 = x_1 + y_1 \geq 8\}$

$\{\mathbf{z_2 = x_1 + y_1}, z_2 = x_1 - y_1\}$

$\{z_3 = 9\}$

$z_4 = g_1 ? z_2 : z_3$

$\{\mathbf{b_1 = z_4 \geq 9}, b_1 = z_4 > 9\}$

$\{\mathbf{z_5 = z_4 - 1}, z_5 = z_4 + 1\}$

$z_6 = b_1 ? z_5 : z_4$

$z_6 \leq 8$

Third step - Repair

```
int f(int x, int y){
    int z;
    if (x + y > 8) {
        z = x + y;
    } else {
        z = 9;
    }
    if (z ≥ 9) {
        z = z − 1;
    }
    assert(z > 8);
    return z;
}
```

SAT solver

SMT solver

$\{ g_1 = x_1 + y_1 > 8 , g_1 = x_1 - y_1 > 8, g_1 = x_1 + y_1 \geq 8\}$

$\{ z_2 = x_1 + y_1, z_2 = x_1 - y_1\}$

$\{ z_3 = 9\}$

$z_4 = g_1 ? z_2 : z_3$

$\{ b_1 = z_4 \geq 9 , b_1 = z_4 > 9\}$

$\{ z_5 = z_4 - 1, z_5 = z_4 + 1\}$

$z_6 = b_1 ? z_5 : z_4$

$z_6 \leq 8$

Repair

c_1 c_2

$\{g_1 = x_1 + y_1 > 8,\ g_1 = x_1 - y_1 > 8,$
$g_1 = x_1 + y_1 \geq 8\}$
c_3

c_4 c_5

$\{z_2 = x_1 + y_1,\ z_2 = x_1 - y_1\}$

c_6

$\{z_3 = 9\}$

c_7 c_8

$\{b_1 = z_4 \geq 9,\ b_1 = z_4 > 9\}$

c_9 c_{10}

$\{z_5 = z_4 - 1,\ z_5 = z_4 + 1\}$

SAT solver

Choose candidate program of ***size*** $= 1$

Blocking clause for specific assignment

Blocking clause for this assignment
And ***all other supersets of changes***

UNSAT / *SAT*
(not a repair) / *(repair found!)*

SMT solver

$z_4 = g_1 ? z_2 : z_3$

$z_6 = b_1 ? z_5 : z_4$

$z_6 \leq 8$

$g_1 = x_1 + y_1 > 8$

$z_2 = x_1 + y_1$

$z_3 = 9$

$b_1 = z_4 \geq 9$

$z_5 = z_4 - 1$

SAT

$c_1 = 0/1$
$c_2 = 0/1$
$c_3 = 0$
$c_4 = 1$
$c_5 = 0$
$c_6 = 1$
$c_7 = 0/1$
$c_8 = 0/1$
$c_9 = 1$
$c_{10} = 0$

UNSAT

Summary

- We suggest a repair method which returns all minimal (bounded) correct programs, in increasing size
  - Based on a given set of mutations
- Minimal mutations: No change is made to the original program unless necessary
- If no repaired program is returned then the given mutations cannot repair the program

Summary

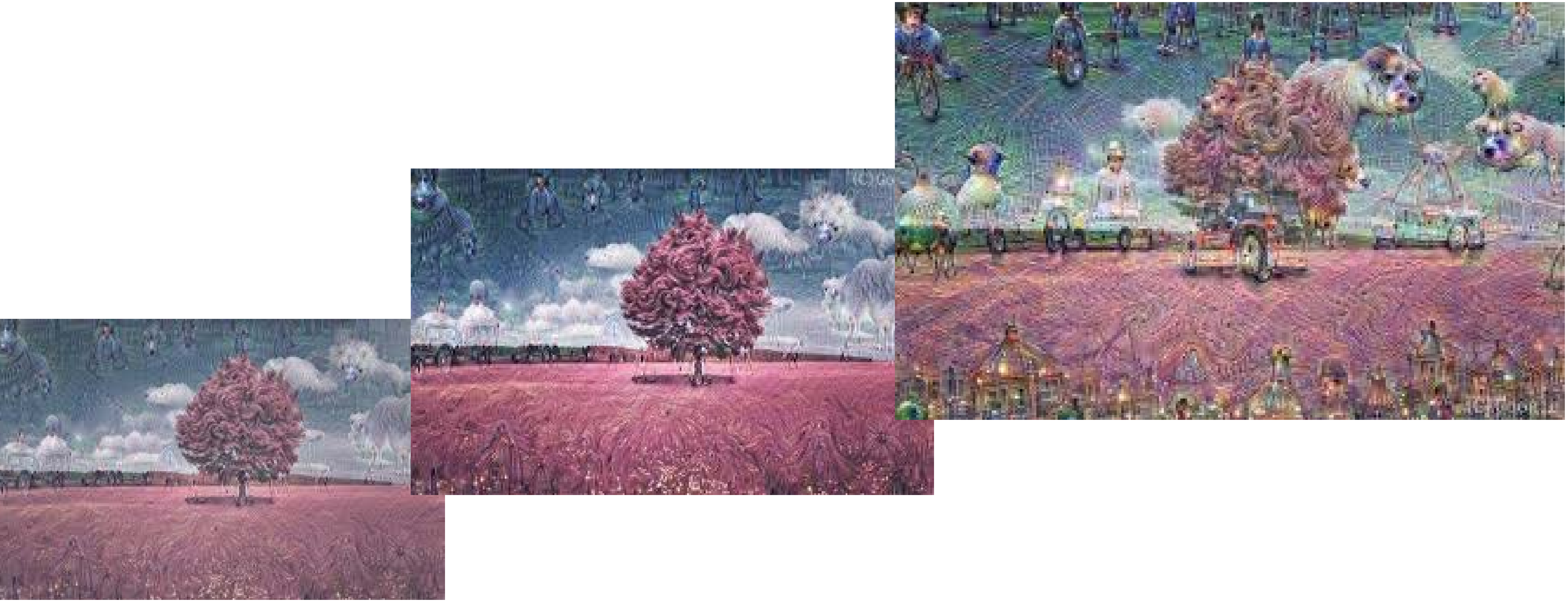
The method can assist a programmer in debugging in initial stages of development

- When bugs are simple, but many

- And also can help beginners
  - Educational tool for students

- Difference analysis can be used to prioritize the returned repaired programs

EVOLVING SOFTWARE



Questions?