Automated Program Repair Using Formal Verification Techniques

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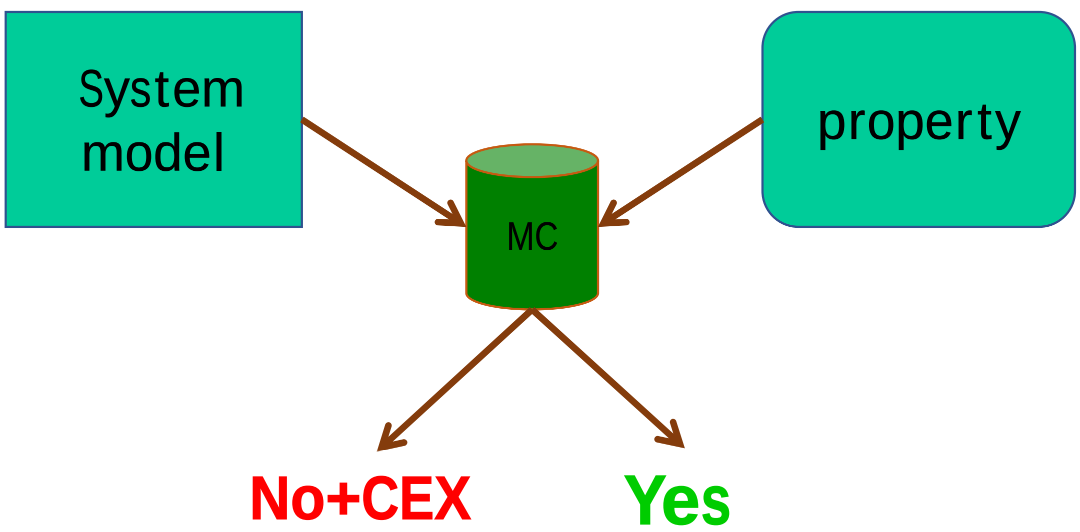
Model Checking

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



Formal automated program repair

- Model checking finds bugs in the program
  - Bug: A program run that violates the specification

- Repair tool automatically suggests repair(s)
  - Repair: Changes to the program code, resulting in a correct program

We present two approaches

- To exploit formal verification techniques for program repair
  - Must Fault Localization for Program Repair
  - Assume, Guarantee or Repair

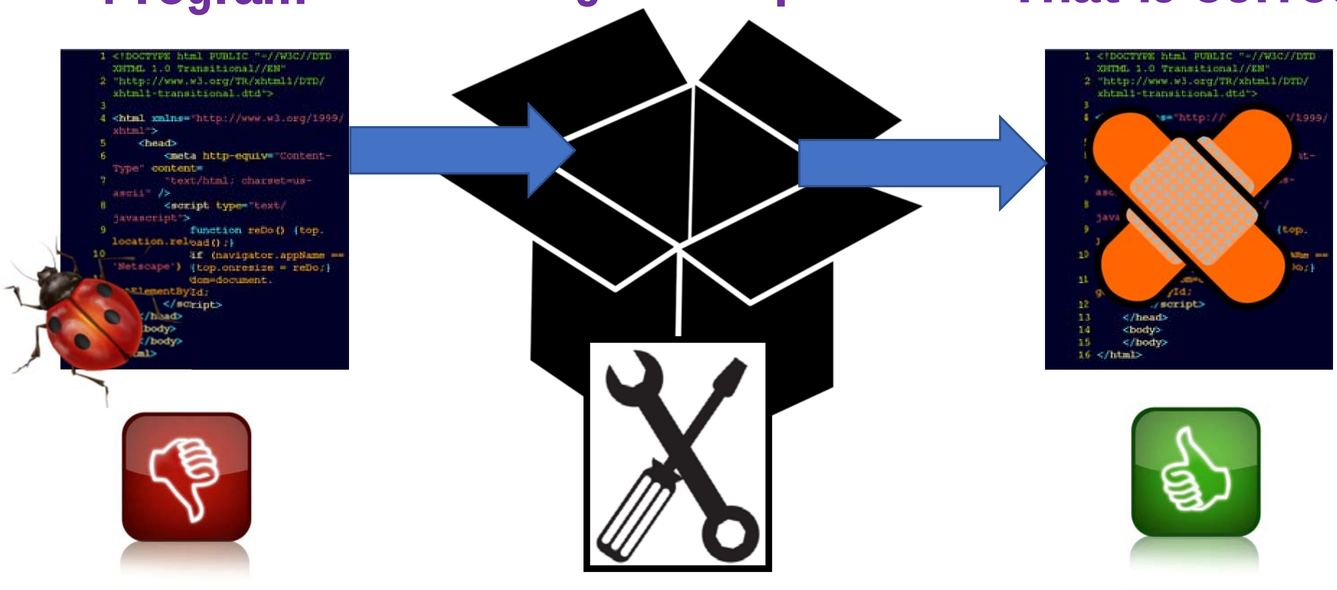
Must Fault Localization for Program Repair

Joint work with Bat-Chen Rothenberg

CAV 2020

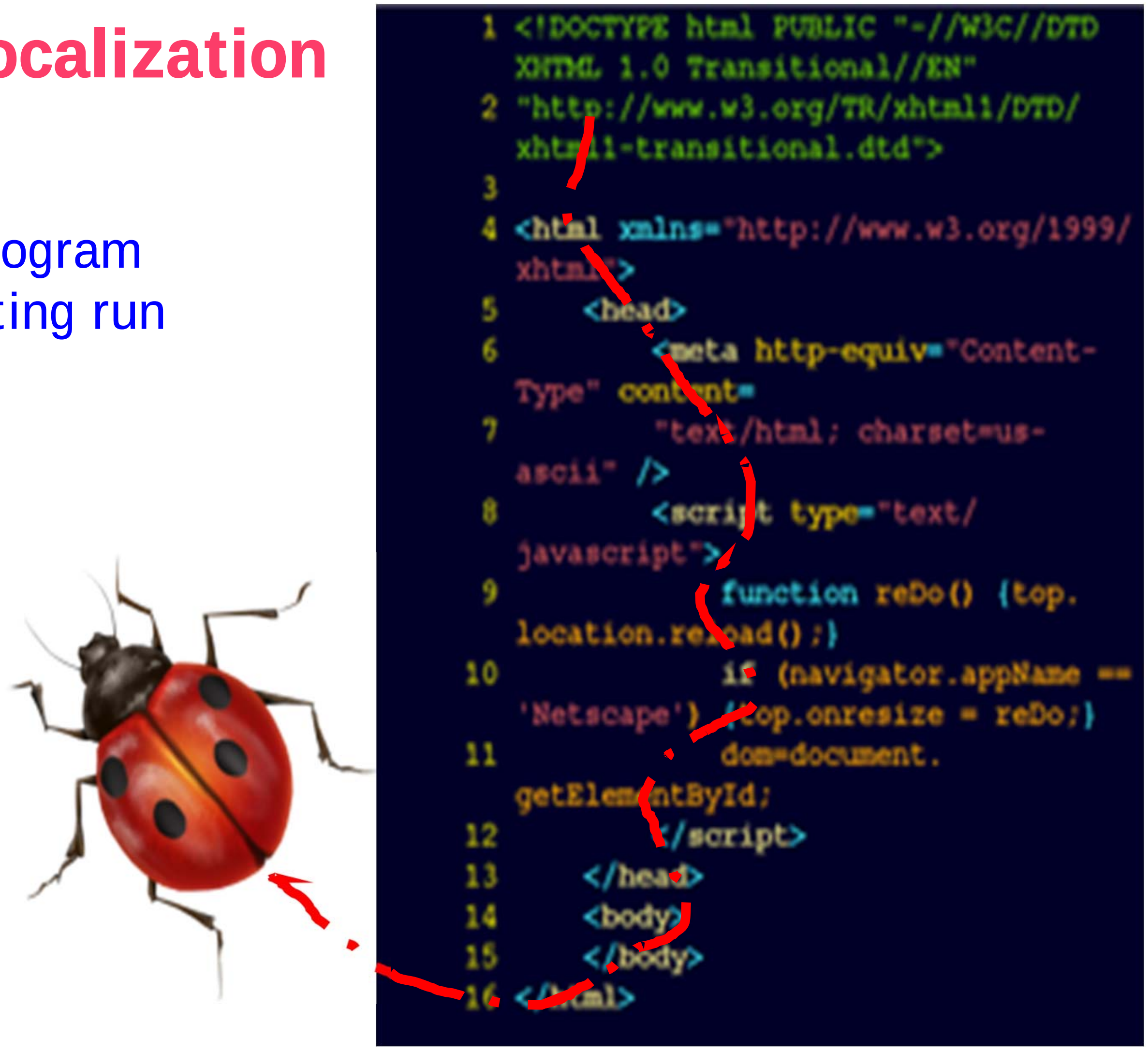
Automated Program Repair

Buggy Program | **Automated Program Repair** | **Patched Program That is Correct**



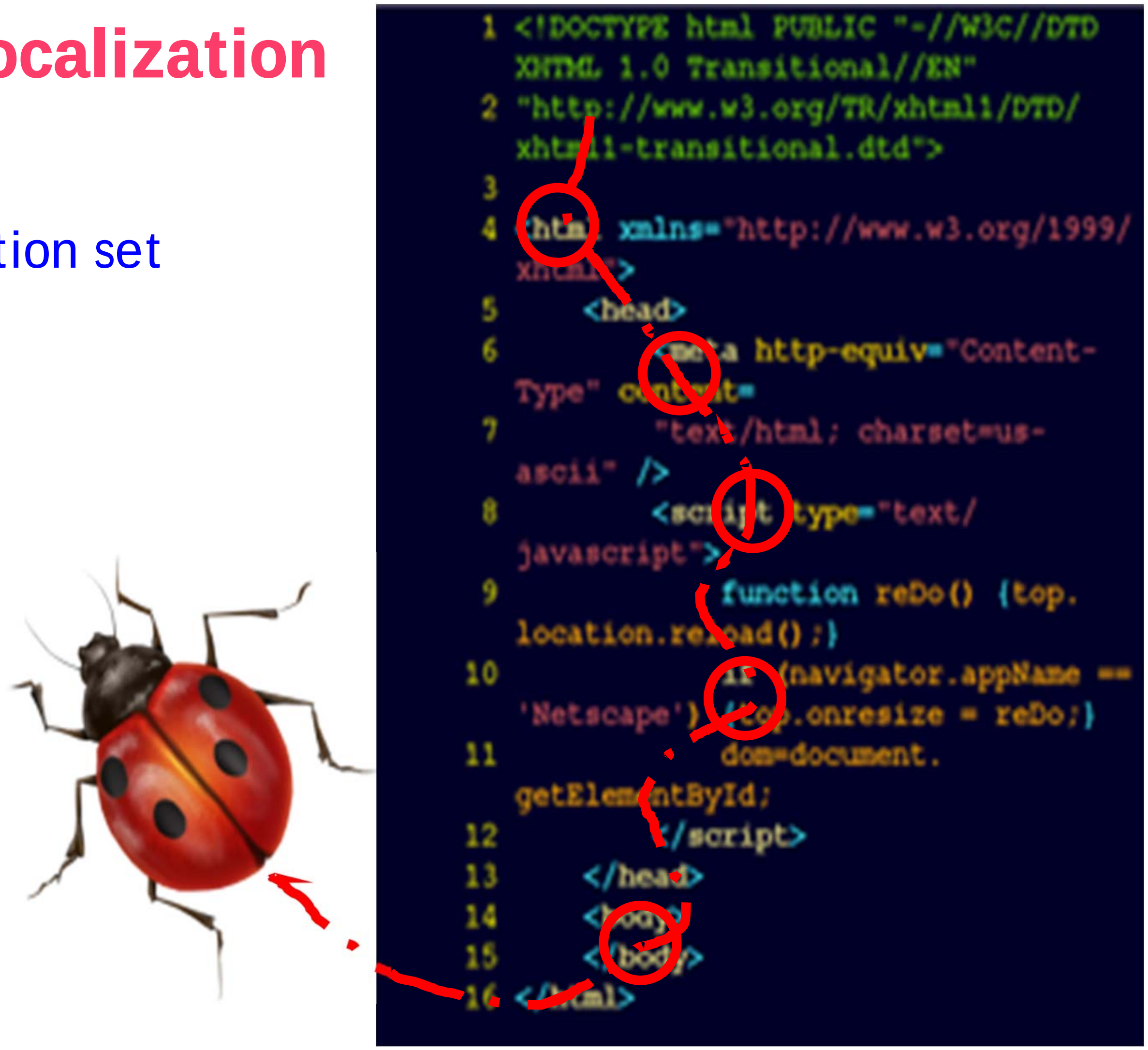
Fault Localization

A buggy program
with violating run



Fault Localization

Fault location set



Fault Localization

Repair

Fault localization

- Fault localization should focus the programmer's attention on locations that are relevant for the bug

- Bad fault localization:
  - Too restrictive might miss a potential repair
  - Too permissive will cause an extra search work

Fault localization

- Often – fault localization algorithms return a set of locations that **may** be relevant
  - No guarantee that all returned locations are relevant
  - Nor that every relevant location is returned
- We suggest a novel notion of **must** fault localization

Repair scheme

An important notion:

- Repair scheme:

  Identifies the changes to program statements, allowed by repair

Repair scheme example

- Repair scheme **S_{mut}**
  - Allows syntactic replacement of operators on the right-hand-side of assignments and in conditions
  - For example,
    $+ \rightarrow -$
    $> \rightarrow <$
    $c \rightarrow c+1$

Must fault localization

- Must fault localization algorithm:
  returns a must location set
  - for every buggy program and every bug

- Must location set:
  Contains at least one location from any successful repair for the bug
  $\Rightarrow$ It is impossible to fix the bug using only locations outside this set
  $\Rightarrow$ Any repair for the bug **must** use at least one location from this set

Must and Repair scheme

- Must notions depend on the chosen repair scheme
- A location set might be must for one repair scheme and non-must for another

In this work

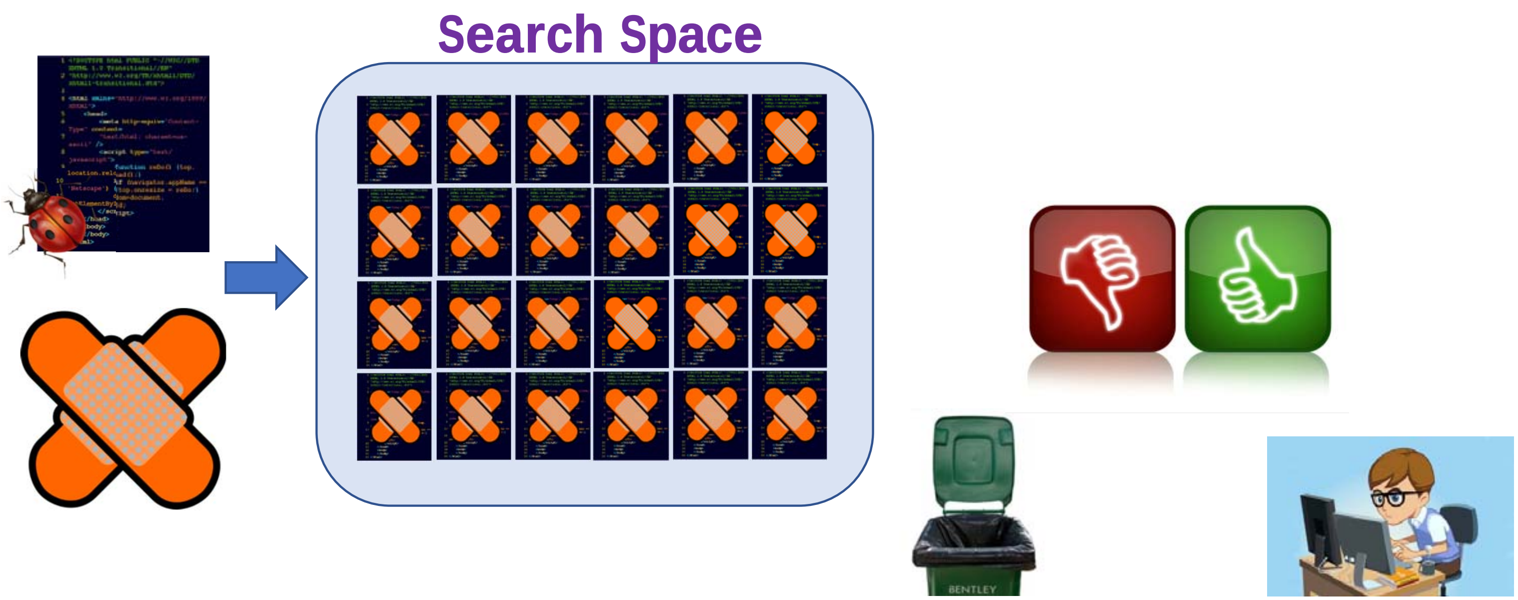
- We develop a fault localization algorithm
- Prove that it is must with respect to S_{mut}
- Implement it within the repair tool AllRepair
- Show significant speedups

Our setting:
Formal Automated Program Repair

Specification

- **Formal specification:** program should meet the specification **for all inputs**
  - pass (**bounded**) formal verification

Our setting:
Search-Based Program Repair



Generate and Validate

Algorithm for must fault localization

- By example

Example: Buggy program

```
proc. foo(x, w)
t:= 0
y:= x-3
z:= x+3
if (w>3) then
    t:= z+w
    assert (t<x)
    y:= y+10
assert (y>z)
```

Example: buggy program with buggy run

proc. foo(x, w)	I = x←0, w←0
t:= 0	t ← 0
y:= x-3	y ← -3
z:= x+3	z ← 3
if (w>3) then	¬(0 > 3)
t:= z+w	
assert (t<x)	
y:= y+10	
assert (y>z)	**¬(-3 > 3)** assertion violation for I

Example: Program formula (SSA)

proc. foo(x, w)

1. t:= 0
2. y:= x-3
3. z:= x+3
4. if (w>3) then
5.   t:= z+w
6.   assert (t<x)
7.   y:= y+10
8. assert (y>z)

φ_{foo} = {

$t_0 = 0$

$y_0 = x_0 - 3$

$z_0 = x_0 + 3$

$\mathbf{g_0 = w_0 > 3}$

$t_1 = z_0 + w_0$

$y_1 = y_0 + 10$

$t_2 = (g_0 ?\ t_1 : t_0)$

$\mathbf{y_2 = (g_0 ?\ y_1 : y_0)}$

$\neg\,\mathbf{(y_2 > z_0)} \vee \neg(g_0 \rightarrow t_1 < x_0)$

}

Example: Program formula (SSA) with satisfying assignment

φ_{foo} = {
$t_0 = 0$
$y_0 = x_0 - 3$
$z_0 = x_0 + 3$
$g_0 = w_0 > 3$
$t_1 = z_0 + w_0$
$y_1 = y_0 + 10$
$t_2 = (g_0 ?\ t_1 : t_0)$
$y_2 = (g_0 ?\ y_1 : y_0)$
$\neg\, \mathbf{(y_2 > z_0)} \vee \neg(g_0 \rightarrow t_1 < x_0)$
}

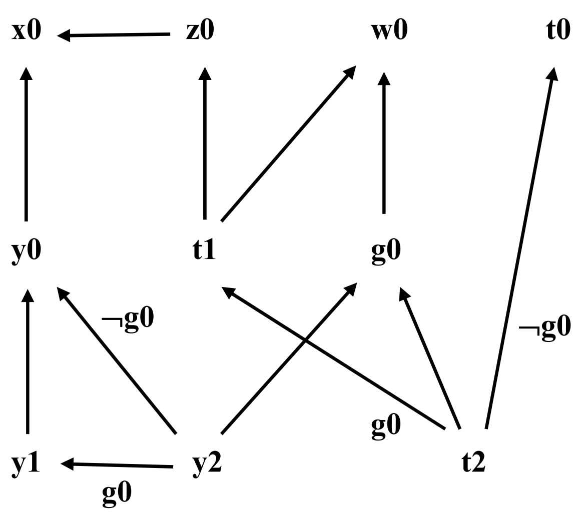
I = $x_0 \leftarrow 0$, $w_0 \leftarrow 0$
$t_0 \leftarrow 0$
$y_0 \leftarrow -3$
$z_0 \leftarrow 3$
$\mathbf{g_0 \leftarrow (0 > 3) = false}$

...

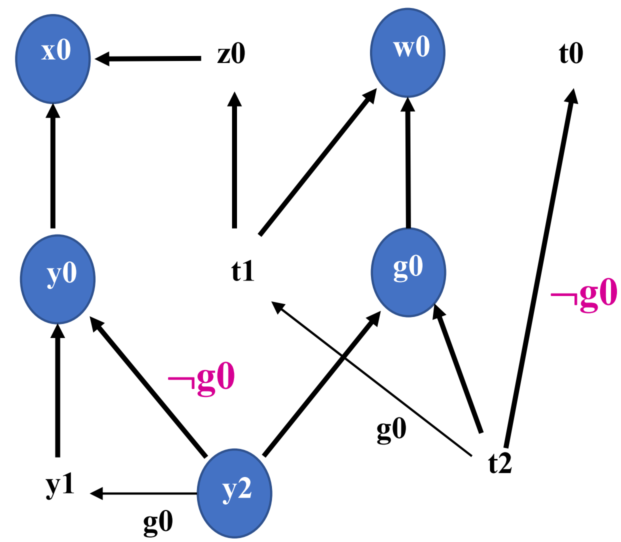
$y_2 \leftarrow -3$
$\neg\mathbf{(-3 > 3)}$ assertion violation for I

Computing fault localization using dependency graphs

φ_{foo} = {
$t_0 = 0$
$y_0 = x_0 - 3$
$z_0 = x_0 + 3$
$g_0 = w_0 > 3$
$t_1 = z_0 + w_0$
$y_1 = y_0 + 10$
$t_2 = (g_0 ?\ t_1 : t_0)$
$y_2 = (g_0 ?\ y_1 : y_0)$
$\neg (y_2 > z_0) \vee$
$\neg (g_0 \rightarrow t_1 < x_0)$
}



Static dependency graph



Dynamic dependency graph
For bug in which **g_0 is false**

Must location set, based on dynamic slicing

φ_{foo} = {
$t_0 = 0$
$y_0 = x_0 - 3$
$z_0 = x_0 + 3$
$g_0 = w_0 > 3$
$t_1 = z_0 + w_0$
$y_1 = y_0 + 10$
$t_2 = (g_0 ?\ t_1 : t_0)$
$y_2 = (g_0 ?\ y_1 : y_0)$
$\neg (y_2 > z_0) \vee \neg(g_0 \rightarrow t_1 < x_0)$
}

$slice_\mu(y_2) \cup slice_\mu(z_0) =$
$\{ y_2=(g_0?\ y1:y0),\ \ y_0=x_0-3,\ \ g_0=w_0>3 \} \cup$
$\{ z_0=x_0+3 \}$

Must fault location set:
set of statements from the program
{ y:= x-3, z:=x+3, g:= w>3 }

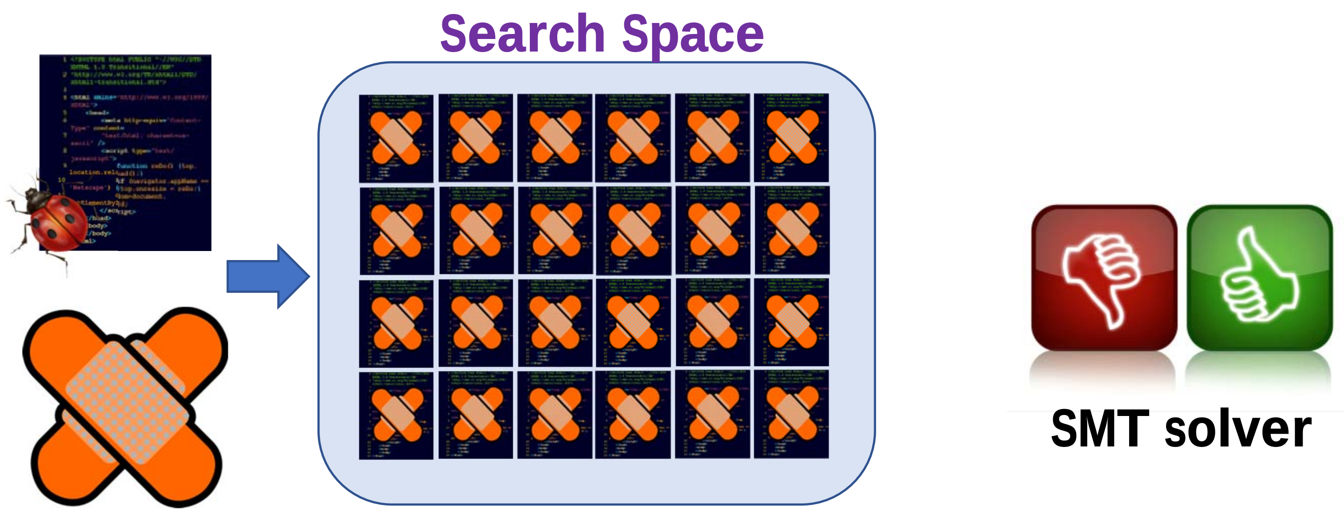
Implementing must fault localization

We implemented our must fault localization algorithm

- within the AllRepair tool

- AllRepair is based on generate – validate
- It returns all minimal repairs from the search space
  - Based on S_{mut}
  - Minimal with respect to the number of changes (mutations) applied to the code

Sound and Complete Mutation-Based Program Repair: AllRepair



Making AllRepair more efficient

Goal: reducing the search space

1. When a **correct mutated program** is generated (Validate succeeds)
   - Eliminate non-minimal correct mutated programs

2. When a **buggy mutated program** is generated (Validate fails)
   - Eliminate “similar” buggy mutated programs

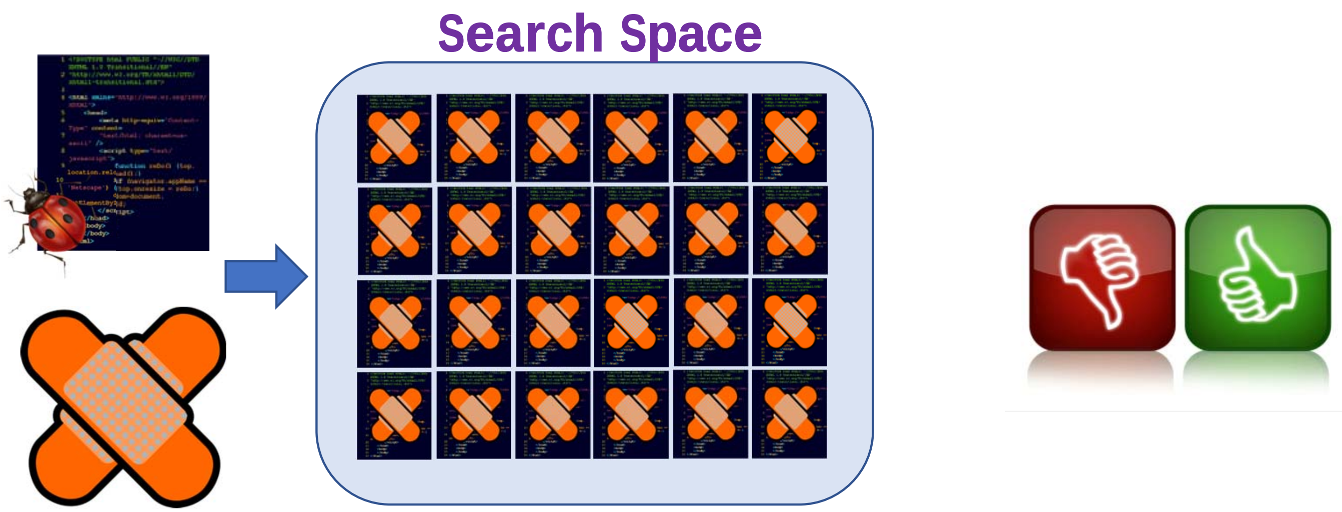
Buggy mutated program

Unsuccessful repair:
Buggy mutated program P_M is generated

Elimination:

- Find a must location set F for the bug in P_M
  - F is a set of statements that guarantee the bug, if not changed
- Eliminate from the search space any mutated program, containing F

Adding must fault localization to program repair: FL-AllRepair



Theorem: FL-AllRepair is sound and complete

That is, no good repair is eliminated by our pruning of the search space

Experimental results - Benchmark

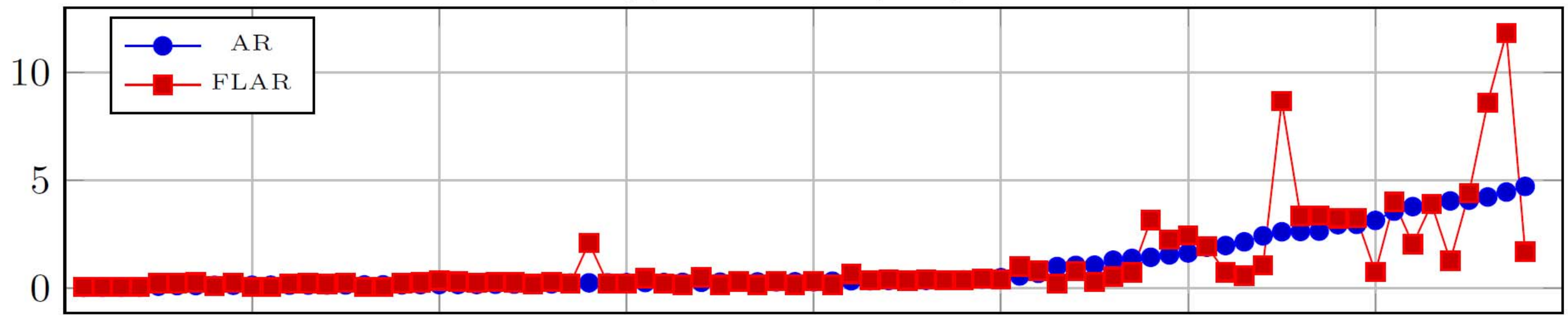
- TCAS
  traffic collision avoidance system for aircrafts

- Codeflaws
  solutions submitted by programmers to the programming contest site Codeforces
  Loops were unwound 2, 5,8, 10 times

Specification: Checking equivalence to a correct version

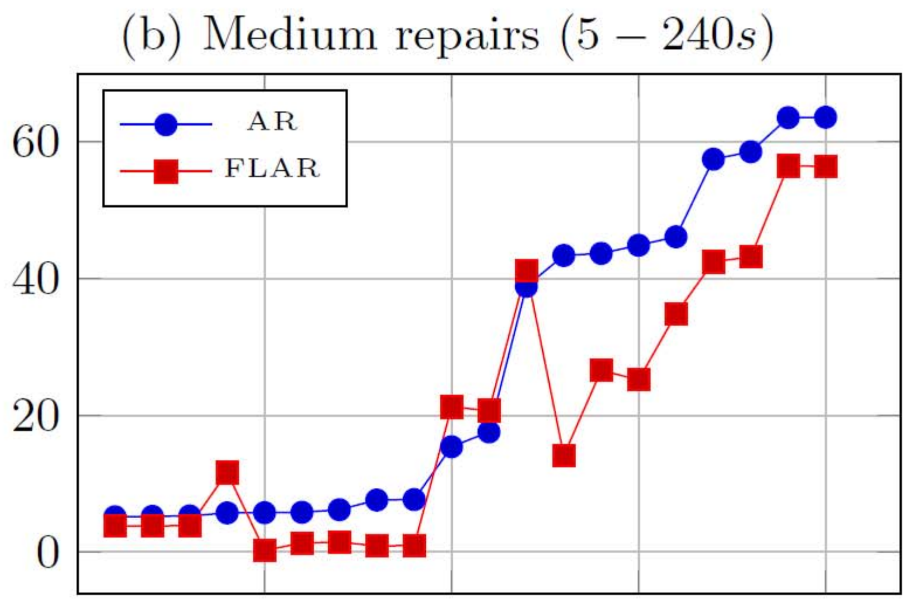
Comparing times of **AllRepair** and **FL-AllRepair**

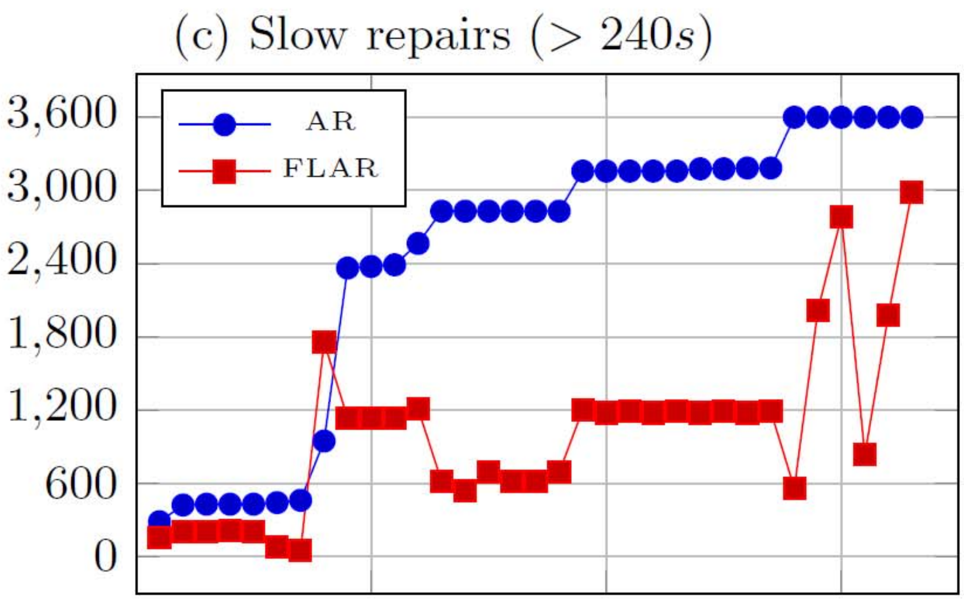
(a) Fast repairs (< 5s)



Each x value represents a single repair; y represent the time in seconds
Timeout of 10 minutes; at most 2 mutations

Comparing times of **AllRepair** and **FL-AllRepair**





x values represent a single repair; y represent the time in seconds

Timeout of 10 minutes; at most 2 mutations

Summary

- A novel **must** fault localization
  - With respect to a repair scheme
- “must” and not “may”: you **must** change at least one of the lines returned
- Even though fault localization is must, its computation is relatively cheap

Summary

- Our must fault localization significantly speeds up the mutation-based automated program repair tool: AllRepair
  - By pruning the search space
  - No good potential repair is lost!

Assume, Guarantee or Repair

Joint work with

Hadar Frenkel, Corina Pasareanu, Sarai Sheinvald

TACAS 2020

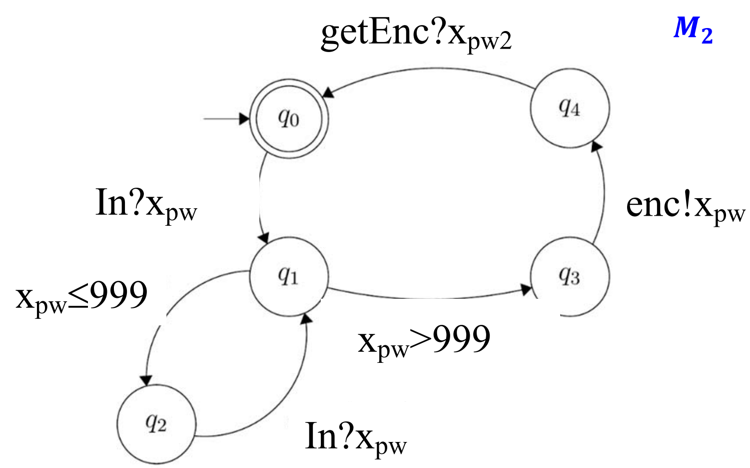
Goal

- Exploit the partition of the system into components
- Compositional model checking verifies small components and conclude the correctness of the full system
- If a bug is found, repair is applied to one of the components

Communicating systems

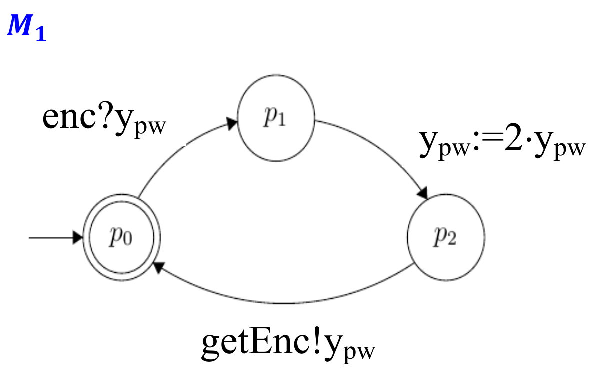
- C-like programs
- Each component is described as a control-flow graph (automaton)
- Enable using automata learning algorithms

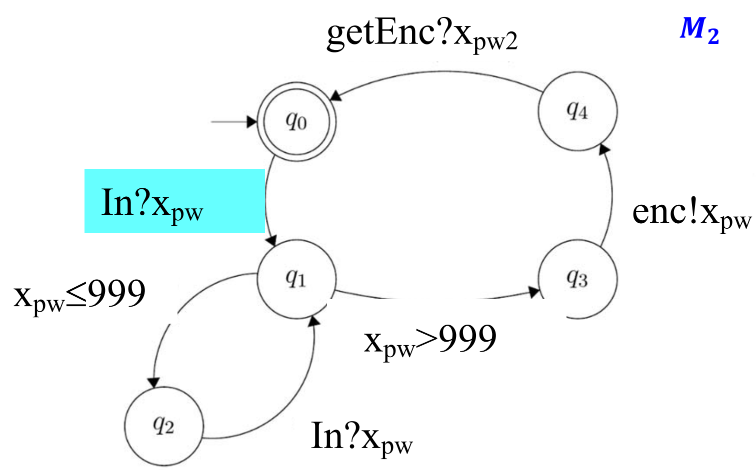
```
while (true)
   pass = readInput;
   while (pass ≤ 999)
      pass = readInput;
   pass2 = encrypt(pass);
```



Example

- Components synchronize over common channels





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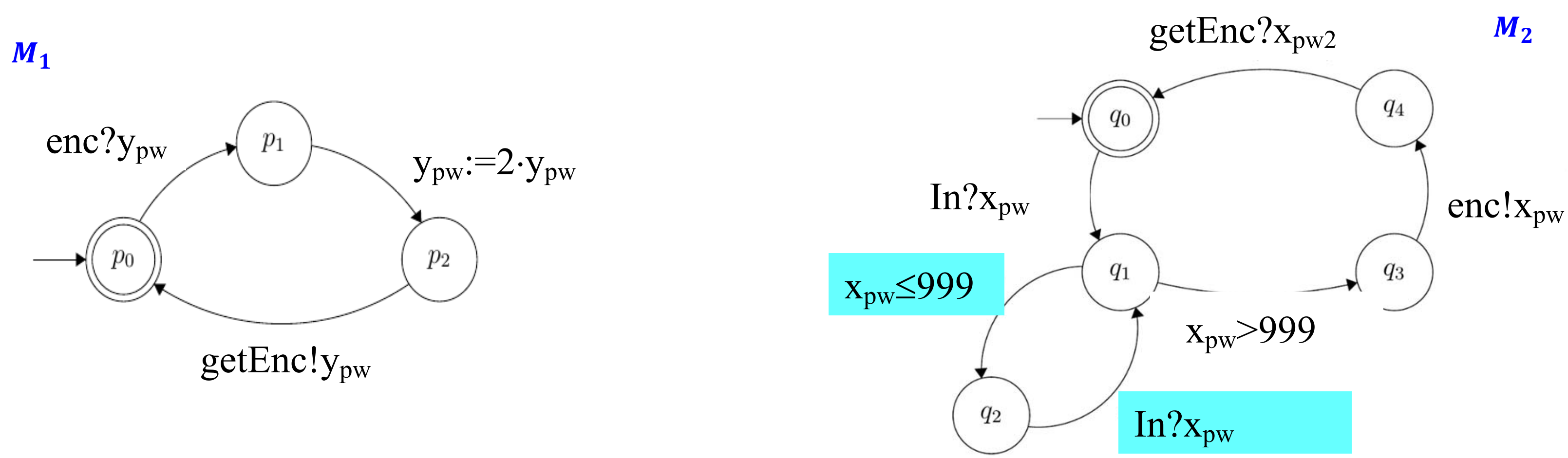

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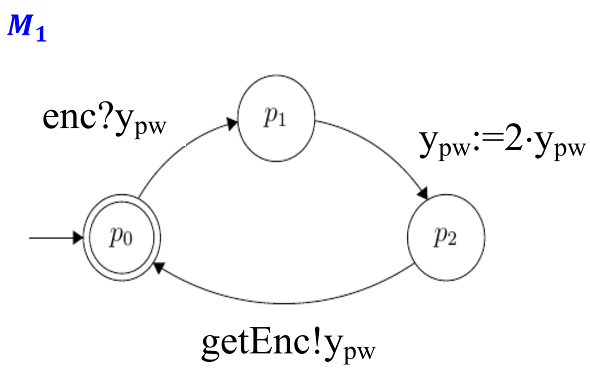

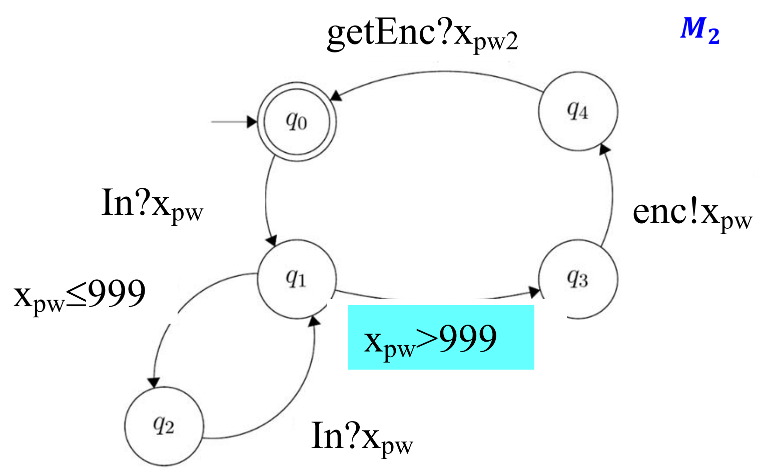

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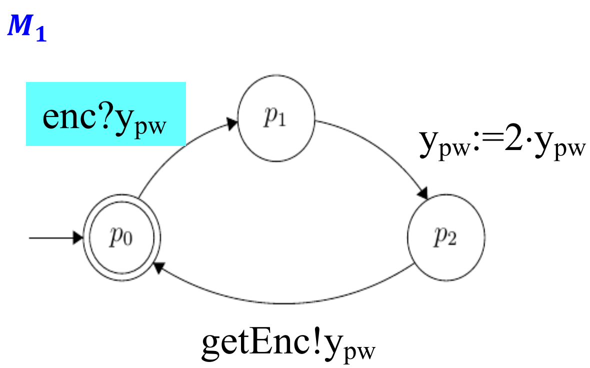

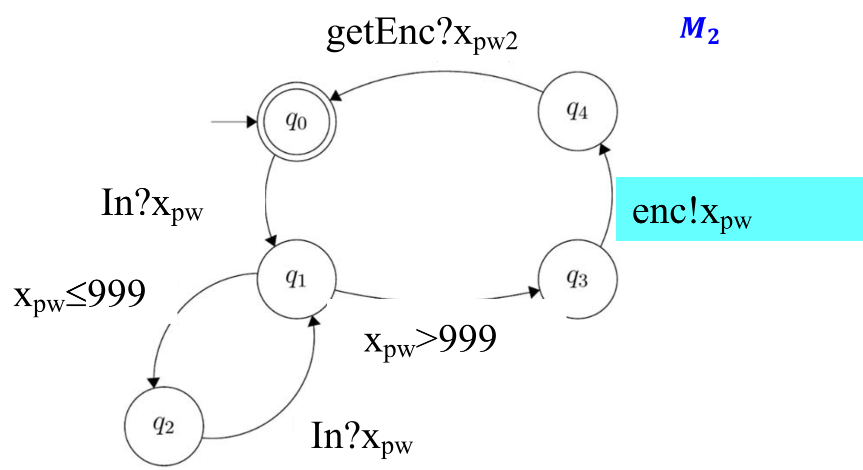

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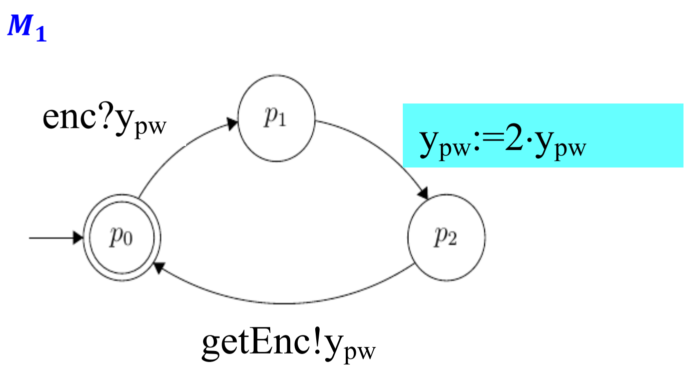

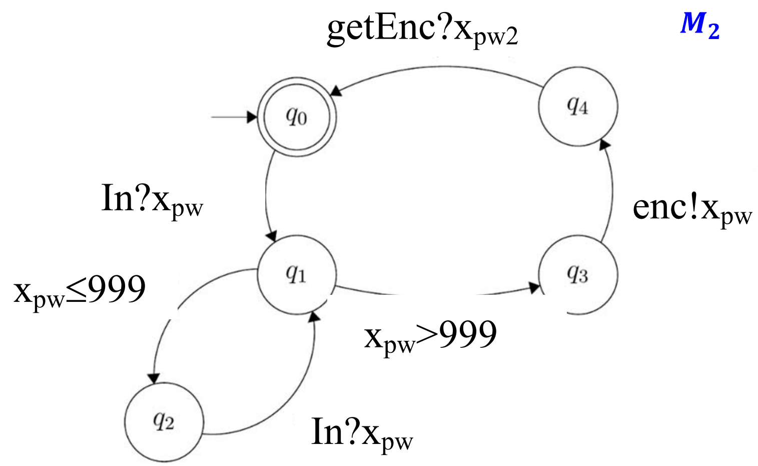

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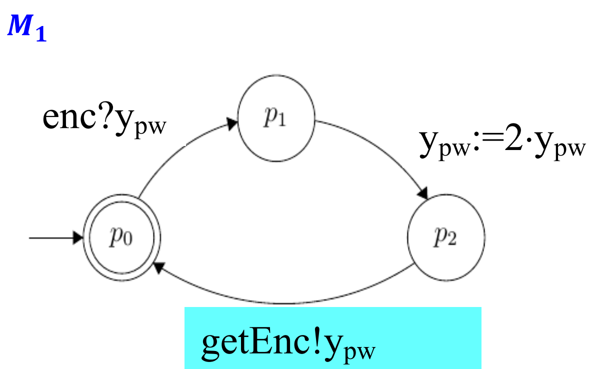
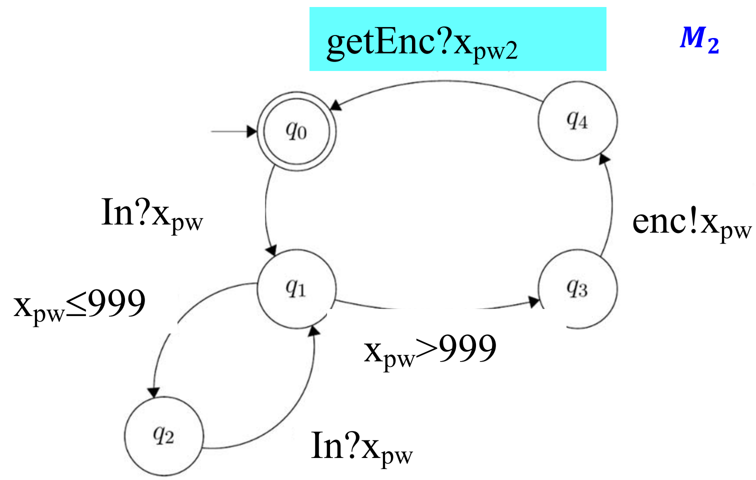
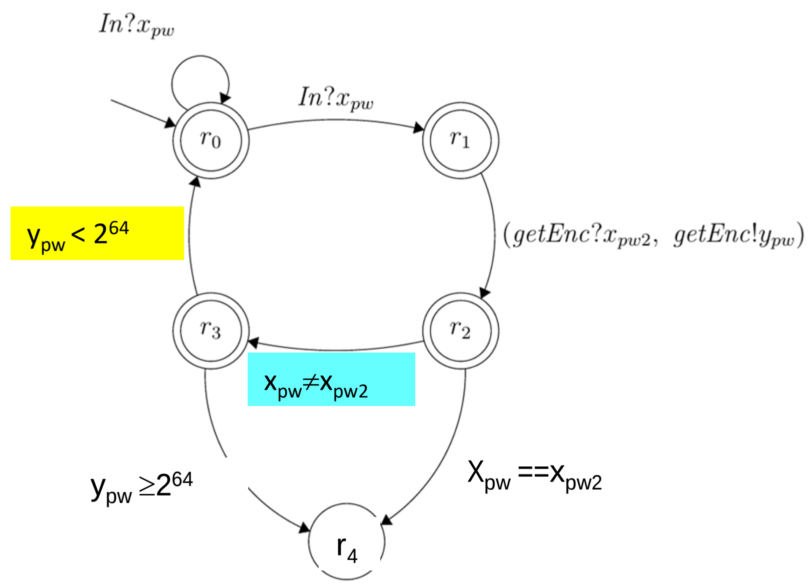




Specifications

- Safety requirements – given as an automaton
- Behavior of the program through time
- "the entered password is different from the encrypted password"
- "there is no overflow"



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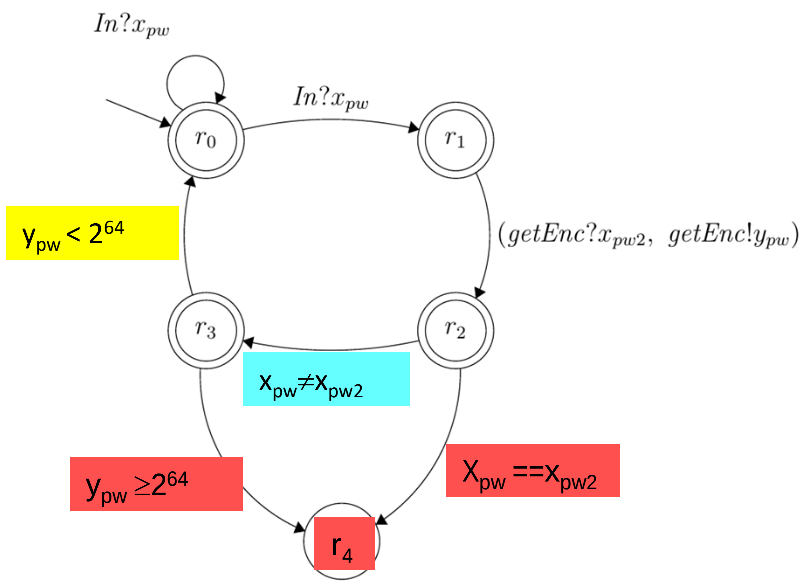
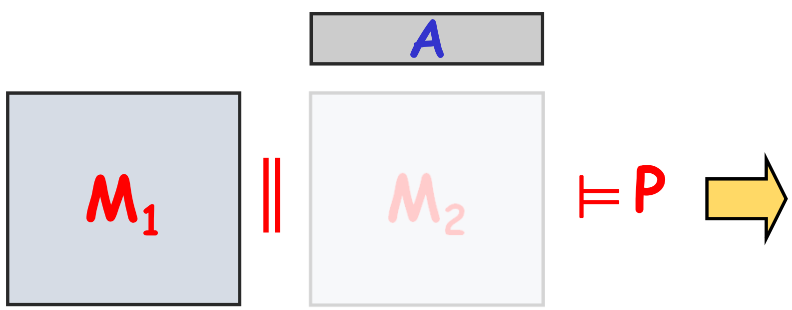


Assume-Guarantee (AG) Rule

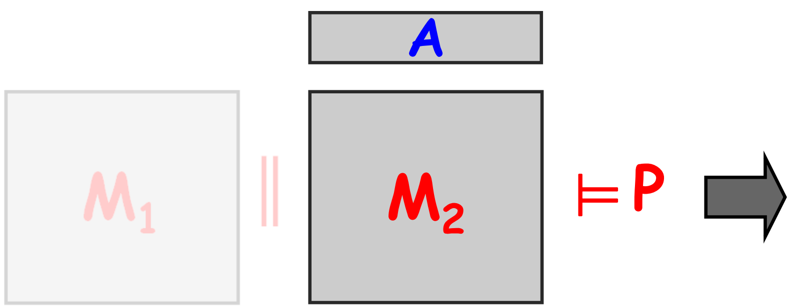
1. check if a component M_1 **guarantees** P when it is a part of a system satisfying **assumption** A



$$\frac{A \,\|\, M_1 \models P}{M_1 \,\|\, M_2 \models P}$$

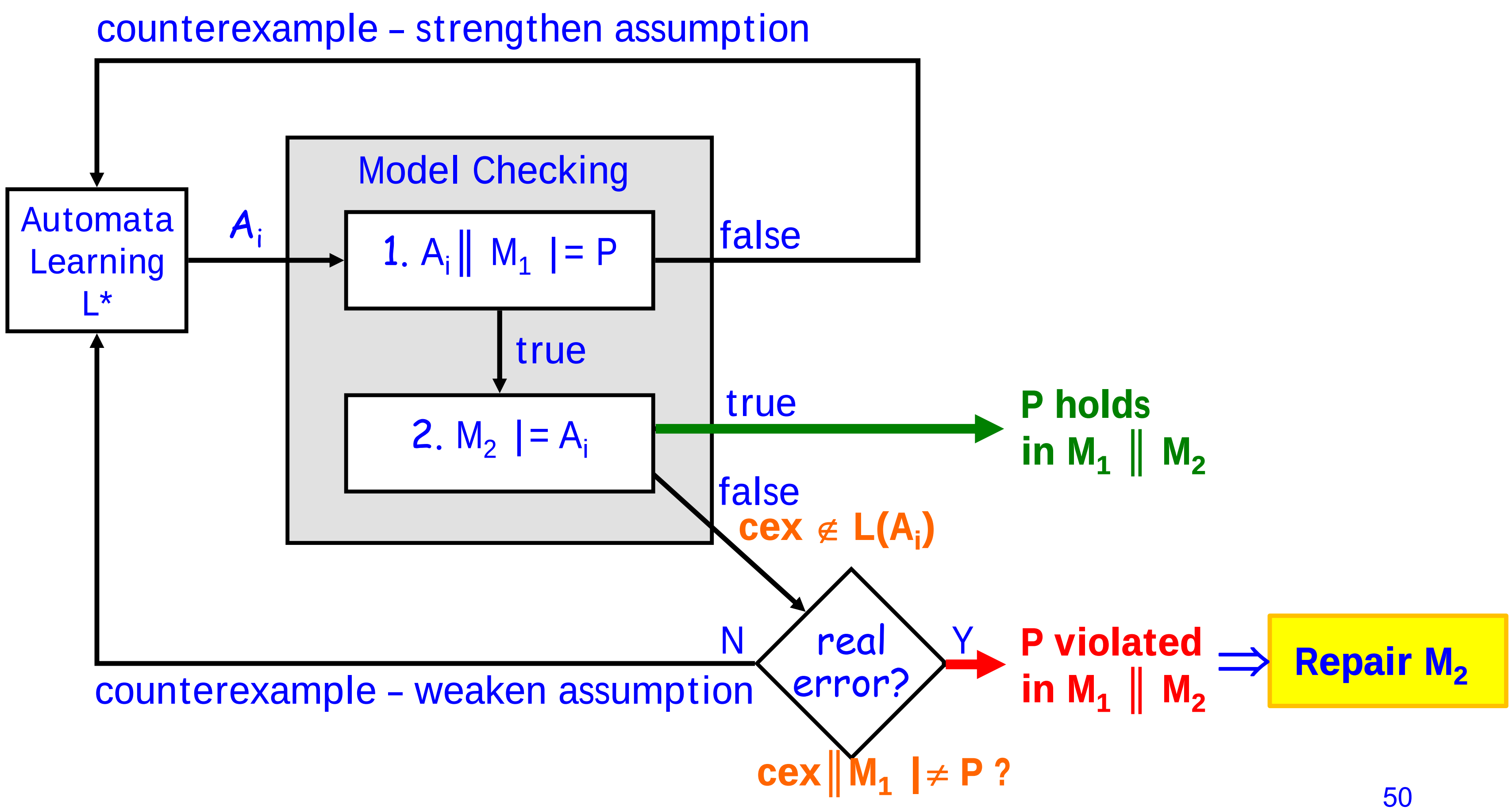
Assume-Guarantee (AG) Rule

1. check if a component M_1 **guarantees** P when it is a part of a system satisfying **assumption** A
2. show that the other component M_2 (the environment) satisfies A



$$\frac{A \parallel M_1 \models P \qquad M_2 \models A}{M_1 \parallel M_2 \models P}$$

Assume Guarantee or Repair



Semantic repair
(cex contains constraint)

- AGR returns a counterexample **t** (for $x_{pw} = 2^{63}$), which contains constraints
- φ_t a formula (in SSA) representing **t**

  $\varphi_t = (x_{pw}>999) \wedge (y_{pw}=x_{pw}) \wedge (y'_{pw}=2 \cdot y_{pw}) \wedge (x_{pw2}=y'_{pw}) \wedge (x_{pw} \neq x_{pw2}) \wedge (y'_{pw} \geq 2^{64})$

- Goal:
  to make the counterexample infeasible by adding another constraint $\mathcal{C}$ to it
  - $(\varphi_t \wedge \mathcal{C} \rightarrow \text{false})$
- Using abduction

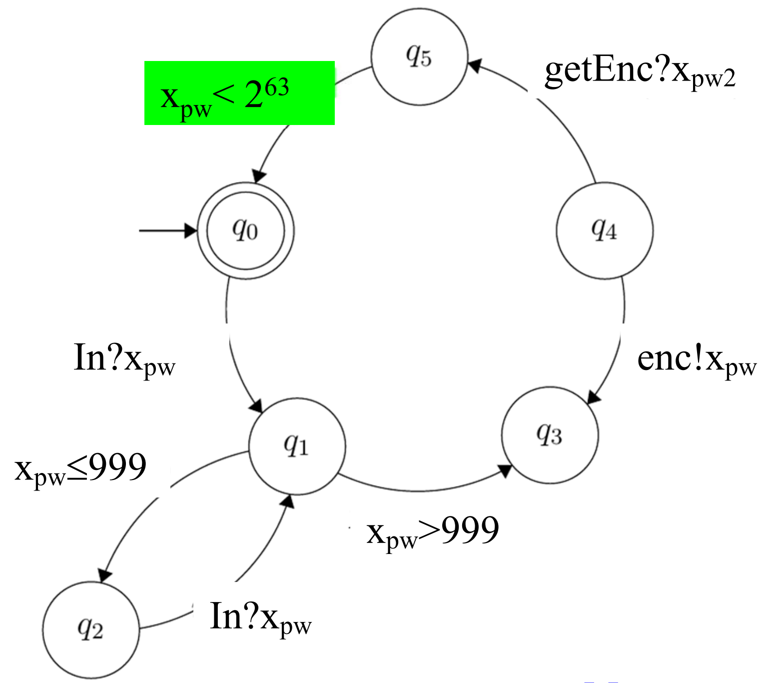
Semantic repair

- Using abduction to repair M_2
- Find $\mathcal{C}$ over the variables of M_2 only such that $(\varphi_t \wedge \mathcal{C} \rightarrow \text{false})$

- $\mathcal{C} = \forall y_{pw} \forall y'_{pw} (\neg\varphi_t)$

- After quantifier elimination and simplification we get:
- $\mathcal{C} = \mathbf{(x_{pw} < 2^{63})}$

Repair



M′2

```
while (true)
   pass = readInput;
   while (pass ≤ 999)
      pass = readInput;
   pass2 = encrypt(pass);
   assume (pass < 2^63)
```

Syntactic repair

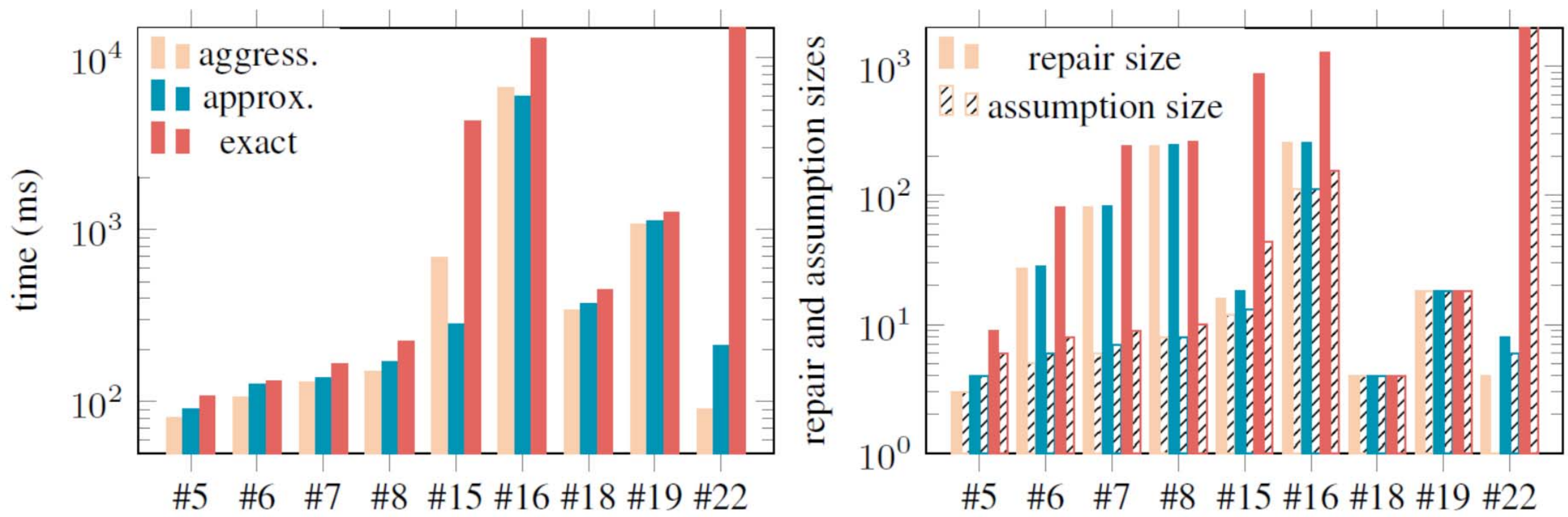
(cex contains no constraints)

- The counterexample t contains no constraint
  - It consists of communication actions and assignments
- Abduction will not help

3 methods to removing counterexample t:

- Exact: remove exactly t from M_2
- Approximate:
- Aggressive:

Comparing Repair Methods (logarithmic scale)



#15, #16, #18, #19 apply also abduction

Adapting L* for communicating C programs

L* is supposed to learn a regular language, over finite alphabet

Our setting:

- Infinite-state programs with first-order constraints:
  - L* Learns words over alphabet including statements in the code:
    assignment, communication action, constraints

- We identify a target language for L*, which is regular:
  - The set of words in M2: sequences of statements

Summary

- Learning-based Assume Guarantee algorithm for infinite-state communicating programs
  - Adjustment of L* for handling infinite-state systems
- Incremental use of subsequent L* applications
- AGR often produces small assumptions, much smaller than M_2
- Semantic and syntactic repair

Summary

- Two approaches to automatic program repair
  - based on formal method technologies

Thank you