Automatic Testing and Fixing of Programs with Contracts

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Design by contract

- Contracts

```
LINKED_LIST . index_of (v: G; i: INTEGER_32): INTEGER_32
        -- Index of `i'-th occurrence of item identical to `v'.
        -- 0 if none.
    require
        positive_occurrences: i > 0
    ensure
        non_negative_result: Result >= 0
```

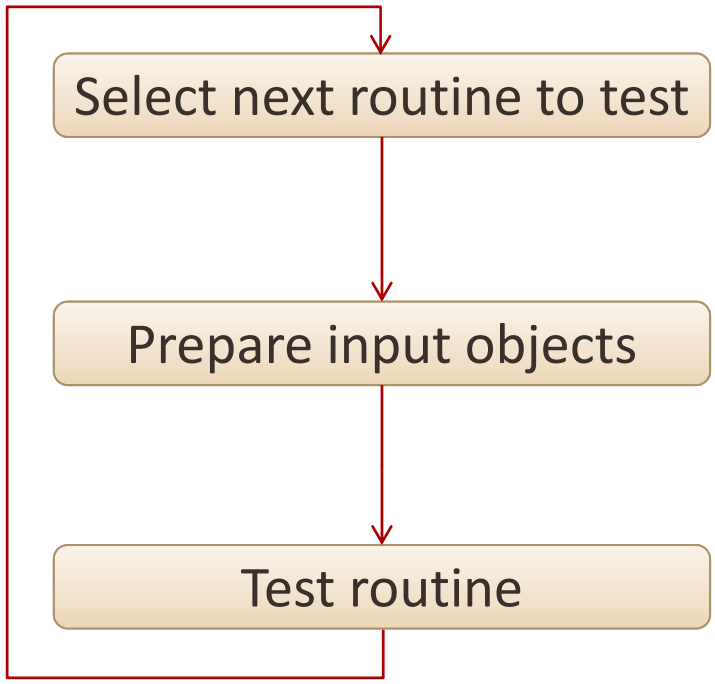
- Applications
  - Specification
  - Documentation
  - Testing & fixing

Automatic (random) testing

- Testing
  - Input
  - Oracle

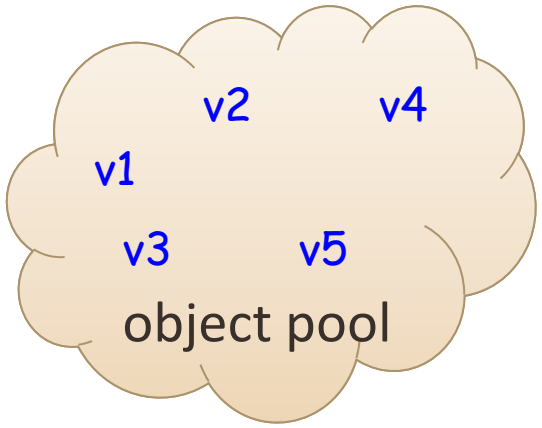
- **AutoTest**: Automatic testing programs with contracts
  - Precondition of the routine under test as the valid input filter
  - Postcondition of the routine as the oracle

The select-prepare-test loop



Sample testing process

```
create {LINKED_LIST [INTEGER]} v1.make
v2 := 1
v1.extend (v2)
v1.wipe_out
v3 := 125
v4 := v1.has (v3)
v5 := v1.count
```



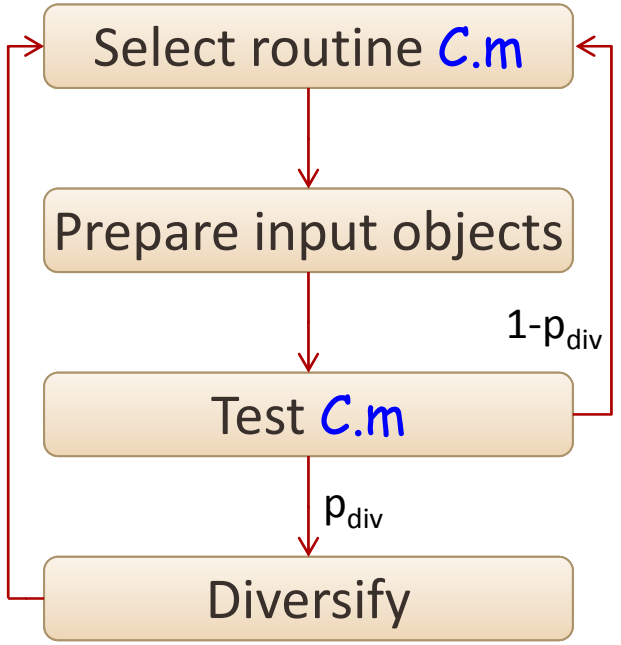
Performance evaluation

- Testing results
  - Precondition of the routine-under-test is violated
    - Invalid test case
  - Precondition of the routine-under-test is satisfied
    - Postcondition satisfied
      - Passing test case
    - Postcondition not established
      - Failing test case (detected fault)

- Evaluation criteria
  - Fault detection rate
  - Input space coverage

Random+ testing

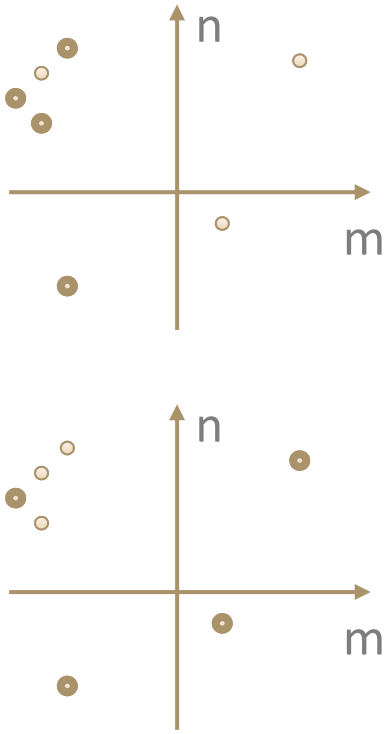
- Essentials
  - Input generation
    - Primitive types:
      random selection + boundary values
    - Reference types:
      constructor calls + random selection
  - Diversification
    - With probability p_{div} after each test



- Result
  - Find faults in widely used, industrial-grade code
  - High fault detection rate in the first a few minutes

Adaptive Random Testing

- Essentials
  - Maintain a list of objects *O* used in testing a routine `r`
  - Select the object with the highest average distance to *O* for the next test of `r`

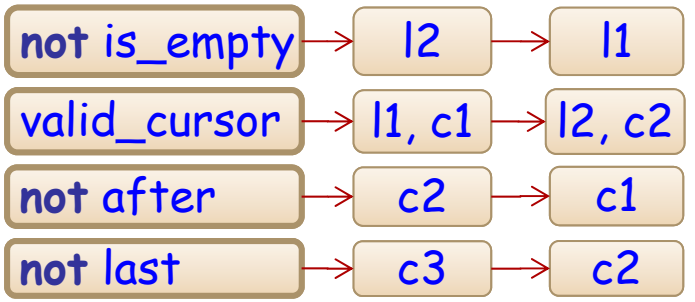


- Result
  - Takes less time and generated tests, on average by a factor of 5, to the first fault

Testing with guided object selection

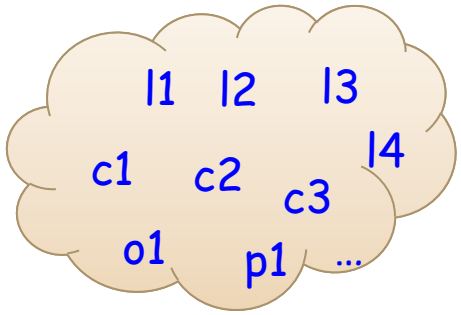
- Essentials
  - Keep track of precondition-satisfying objects
  - Use them with higher probability

LINKED_LIST . remove_right (cursor: CURSOR)



v-pool

- Results
  - 56% of the routines that cannot be tested before are now tested
  - 10% more faults detected in the same time
  - Routines tested 3.6 times more often



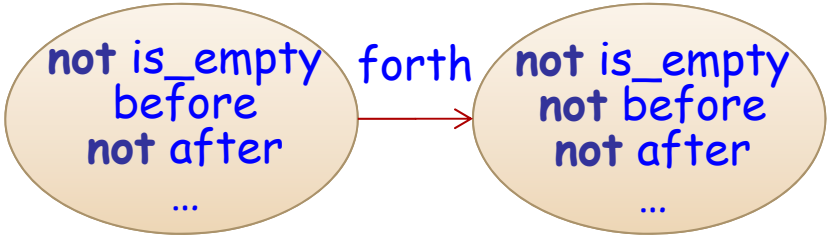
object pool

Stateful testing

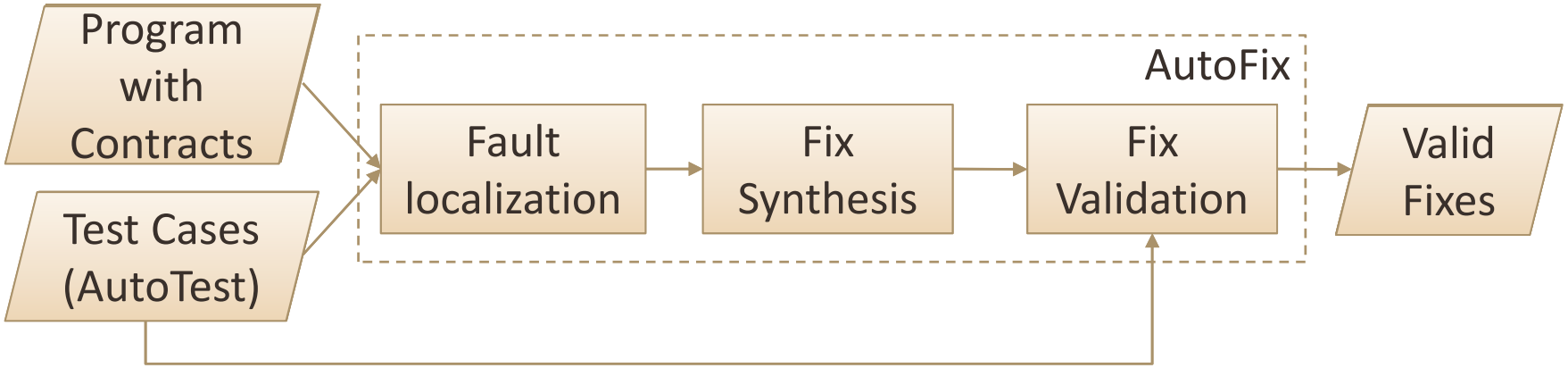
- Essentials
  - Object states in Boolean expressions

```
LINKED_LIST . index_of (v: like item; i: INTEGER_32): INTEGER_32
```

    - before, after, is_empty, i > 0, …
  - Infer preconditions from existing tests
    - Boolean expressions that always hold as preconditions
  - Prepare inputs violating the inferred preconditions
    - Select objects in the object pool
    - Transit objects using object behavioral model
- Result
  - 68% more faults detected with 7% time overhead



Automatic program fixing



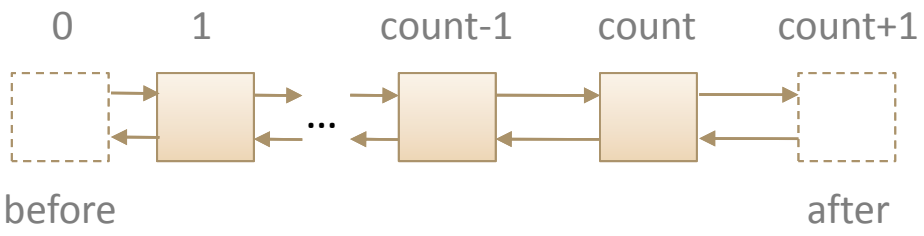
Fault localization

- Model-based
  - Difference between state invariants from passing and failing runs as the fault profile

- Code-based
  - State components as candidate fault causes:
    <exp, loc, val>
  - Suspiciousness scores computed from
    - dyn: frequency of appearance in passing/failing runs
    - cdep: control dependence on the violation position
    - edep: syntactical similarity with the failing assertion

Example

```
1  move_item (v: G)
2        -- from TWO_WAY_SORTED_SET.
3        -- Move `v' to the left of cursor.
4     require v /= Void ; has (v)
5     local idx: INTEGER ; found: BOOLEAN
6     do
7        idx := index
8        from start until found or after loop
9           found := (v = item)
10          if not found then forth end
11       end
12       remove
13       go_i_th (idx)
14       put_left (v)    -- require: not before
15    end
```



- Model-based

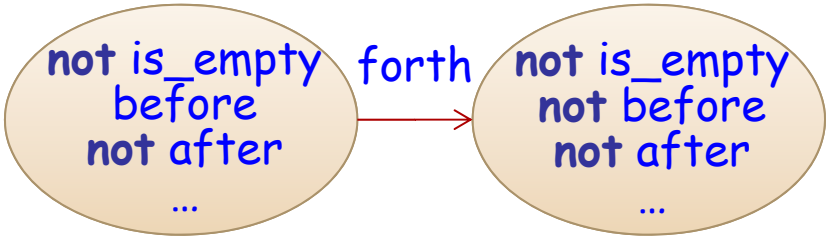
Location	Passing inv.	Failing inv.
…	…	…
L-14	not is_empty not before not after …	not is_empty before not after …
…	…	…

- Code-based

<exp, loc, val>	dyn	cdep	edep	susp.
…	…	…	…	…
<before, L-14, T>	1.5	1	1	**1.13**
…	…	…	…	…
<not after, L-12, T>	0.67	0.86	0.33	**0.22**
…	…	…	…	…

Fix synthesis (1)

- Fixing actions: code necessary for correcting the faulty state (e.g. before @ L-14)
  - Enumeration
    - Identify objects that could be modified to affect the state
    - Enumerate all applicable operations on the objects
  - Object behavioral model



  - Actions: forth, …

Fix synthesis (2)

- Fix schemas capture common fixing styles

```
if fail_condition then
    fixing_action
else
    original_instruction
end
```

```
if fail_condition then
    fixing_action
end
original_instruction
```

- Fix schema instantiation

```
move_item (v: G)
    do
        idx := index
        ...
        remove
        go_i_th (idx)
        put_left (v)
    end
```

```
move_item (v: G)
    do
        idx := index
        ...
        remove
        go_i_th (idx)
        if before then
            forth
        end
        put_left (v)
    end
```

Fix validation and ranking

- Validation
  - Run the patched program against all passing and failing tests, requiring
    - Passing tests still pass
    - Failing tests now pass
- Ranking
  - Static metrics, favoring
    - Simple textual changes
    - Changes close to the failing location
    - Changes involving less original statements
  - Dynamic metric, favoring
    - Behavioral preservation

Experimental evaluation

- **204** randomly detected faults in various programs were used for evaluation
- 86 (or **42%**) out of 204 faults got valid fixes
- 51 (or **59%**) out of 86 faults got proper fixes
- **93%** runs terminated within **15** minutes
- 48 (or **56%**) of the faults that AutoFix managed to fix at least once were fixed in over **95%** of the sessions

Summary

- Contracts promote automatic testing and fixing
  - AutoTest
    - Preconditions as input filters and postconditions as oracles
  - AutoFix
    - Contracts as guarantee of semantic correctness
  - Project web pages:

    http://se.inf.ethz.ch/research/autotest/

    http://se.inf.ethz.ch/research/autofix/

THANKS