HOL-TestGen
An Interactive Test-case Generation Framework

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Outline

State of the Art

“Dijkstra’s Verdict:”

Program testing can be used to show the presence of bugs, but never to show their absence.

- Is this always true?
- Can we bother?

Our First Vision

Testing and verification may converge,
in a precise technical sense:

- specification-based (black-box) unit testing
- generation and management of formal test hypothesis
- verification of test hypothesis (not discussed here)

Our Second Vision

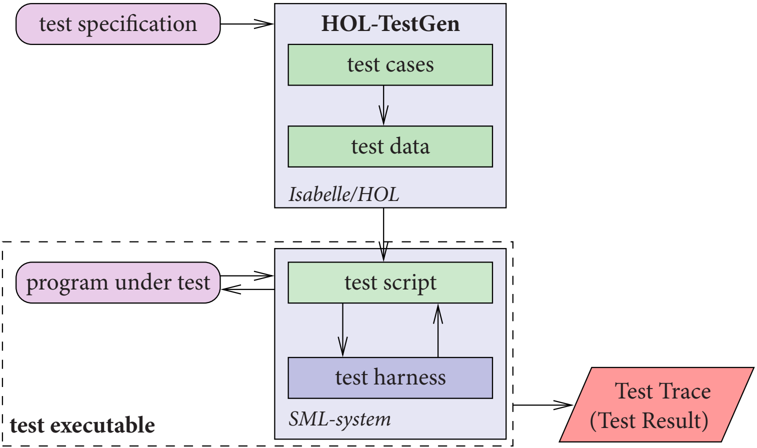
- **Observation:**
  Any testcase-generation technique is based on and limited by underlying constraint-solution techniques.
- **Approach:**
  Testing should be integrated in an environment combining **automated and interactive proof techniques**.
- the test engineer must decide over, abstraction level, split rules, breadth and depth of data structure exploration …
- byproduct: a **verified** test-tool

Outline

Components of HOL-TestGen

- **HOL (Higher-order Logic):**
  - "Functional Programming Language with Quantifiers"
  - plus definitional libraries on Sets, Lists, …
  - can be used meta-language for Hoare Calculus for Java, Z, …
- **HOL-TestGen:**
  - based on the interactive theorem prover Isabelle/HOL
  - implements these visions
- **Proof General:**
  - user interface for Isabelle and HOL-TestGen
  - step-wise processing of specifications/theories
  - shows current proof states

The System Architecture of HOL-TestGen



Outline

The HOL-TestGen Workflow

The HOL-TestGen workflow is basically fivefold:

1. *Step I:* writing a **test theory** (in HOL)
2. *Step II:* writing a **test specification** (in the context of the test theory)
3. *Step III:* generating a **test theorem** (roughly: testcases)
4. *Step IV:* generating **test data**
5. *Step V:* generating a **test script**

And of course:

- building an executable test driver
- and running the test driver

Step I: Writing a Test Theory

- Write **data types** in HOL:

```
theory  List_test
imports Testing
begin

datatype 'a list =
     Nil       ("[]")
   | Cons 'a  "'a list"      (infixr "#" 65)
```

Step I: Writing a Test Theory

- Write **recursive functions** in HOL:

```
consts  is_sorted :: "('a :: ord) list ⇒ bool"
primrec
  "is_sorted  []      = True"
  "is_sorted  (x#xs)  = case xs of
                           []  ⇒ True
                        | y#ys ⇒ ((x < y) ∨ (x = y))
                                  ∧ is_sorted xs"
```

Step II: Write a Test Specification

- writing a **test specification** (TS)
  as HOL-TestGen command:

```
test_spec "is_sorted (prog (l ::('a list)))"
```

Step III: Generating Testcases

- executing the **testcase generator** in form of an Isabelle proof method:

  apply(gen_test_cases "prog")

- concluded by the command:

  store_test_thm " test_sorting "

  ...that binds the current proof state as **test theorem** to the name `test_sorting`.

Step III: Generating Testcases

- The test theorem contains clauses (the **test-cases**):

  $$\begin{array}{l} \text{is\_sorted} \;\; (\text{prog} \;\; []) \\ \text{is\_sorted} \;\; (\text{prog} \;\; [?X1X17]) \\ \text{is\_sorted} \;\; (\text{prog} \;\; [?X2X13, \; ?X1X12]) \\ \text{is\_sorted} \;\; (\text{prog} \;\; [?X3X7, \; ?X2X6, \; ?X1X5]) \end{array}$$

- as well as clauses (the **test-hypothesis**):

  $$\text{THYP}((\exists\, x.\ \text{is\_sorted} \;\; (\text{prog} \;\; [x])) \longrightarrow (\forall\, x.\ \ \text{is\_sorted}\, (\text{prog} \;\; [x]))$$

  $$\vdots$$

  $$\text{THYP}((\forall\, l.\ 4 < |l| \longrightarrow \text{is\_sorted}\, (\text{prog} \;\; l\,))$$

- We will discuss these hypothesises later in great detail.

Step IV: Test Data Generation

- On the test theorem,
  all sorts of logical massages can be performed.
- Finally, a **test data generator** can be executed:

  gen_test_data " test_sorting "
- The test data generator
  - extracts the testcases from the test theorem
  - searches ground instances satisfying the constraints (none in the example)
- Resulting in test statements like:

```
is_sorted (prog [])
is_sorted (prog [3])
is_sorted (prog [6, 8])
is_sorted (prog [0, 10, 1])
```

Step V: Generating A Test Script

- Finally, a **test script** or **test harness** can be generated:

  gen_test_script " test_lists .sml" list " prog

- The generated test script can be used to test an implementation, e.g., in SML, C, or Java

The Complete Test Theory

```
theory List_test
imports Main begin
  consts is_sorted :: "('a :: ord) list ⇒ bool"
  primrec "is_sorted []        = True"
          "is_sorted (x#xs)    = case xs of
                                   [] ⇒ True
                                 | y#ys ⇒ ((x < y) ∨ (x = y))
                                          ∧ is_sorted xs"

  test_spec "is_sorted (prog (l ::('a list)))"
    apply(gen_test_cases prog)
  store_test_thm "test_sorting"

  gen_test_data "test_sorting"
  gen_test_script "test_lists.sml" list" prog
end
```

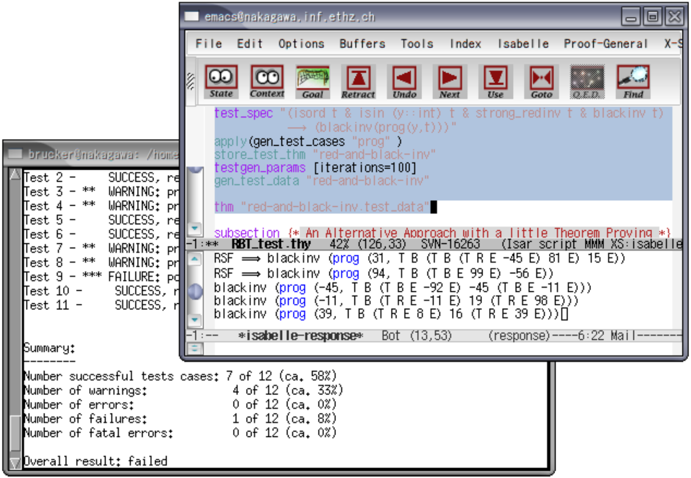
Testing an Implementation

Executing the generated test script may result in:

```
Test Results:
Test 0 - *** FAILURE: post-condition false, result: [1, 0, 10]
Test 1 -     SUCCESS, result: [6, 8]
Test 2 -     SUCCESS, result: [3]
Test 3 -     SUCCESS, result: []

Summary:
Number successful tests cases:  3 of 4 (ca. 75%)
Number of warnings:             0 of 4 (ca.  0%)
Number of errors:               0 of 4 (ca.  0%)
Number of failures:             1 of 4 (ca. 25%)
Number of fatal errors:         0 of 4 (ca.  0%)

Overall result: failed
```


emacs@nakagawa.inf.ethz.ch
File Edit Options Buffers Tools Index Isabelle Proof-General
State Context Goal Retract Undo Next Use Goto Q.E.D. Find
test_spec "(isord t & isin (y::int) t & strong_redinv t & blackinv t) ⟶ (blackinv(prog(y,t)))"
apply(gen_test_cases "prog")
store_test_thm "red-and-black-inv"
testgen_params [iterations=100]
gen_test_data "red-and-black-inv"
thm "red-and-black-inv.test_data"
subsection {* An Alternative Approach with a little Theorem Proving *}
-1:** RBT_test.thy 42% (126,33) SVN-16263 (Isar script MMM XS:isabelle
RSF ⟹ blackinv (prog (31, T B (T B (T R E -45 E) 81 E) 15 E))
RSF ⟹ blackinv (prog (94, T B (T B E 99 E) -56 E))
blackinv (prog (-45, T B (T B E -92 E) -45 (T B E -11 E)))
blackinv (prog (-11, T B (T R E -11 E) 19 (T R E 98 E)))
blackinv (prog (39, T B (T R E 8 E) 16 (T R E 39 E)))
-1:-- *isabelle-response* Bot (13,53) (response)----6:22 Mail
brucker@nakagawa: /home
Test 2 - SUCCESS, re
Test 3 - ** WARNING: pr
Test 4 - ** WARNING: pr
Test 5 - SUCCESS, re
Test 6 - SUCCESS, re
Test 7 - ** WARNING: pr
Test 8 - ** WARNING: pr
Test 9 - *** FAILURE: po
Test 10 - SUCCESS, r
Test 11 - SUCCESS, r
Summary:

Number successful tests cases: 7 of 12 (ca. 58%)
Number of warnings: 4 of 12 (ca. 33%)
Number of errors: 0 of 12 (ca. 0%)
Number of failures: 1 of 12 (ca. 8%)
Number of fatal errors: 0 of 12 (ca. 0%)
Overall result: failed

Outline

Red-black trees

Goal:

Test if balancing property is preserved by the red-black tree operations.

- part of the SML standard library
- widely used internally in the sml/NJ compiler, e.g., for providing efficient implementation for Sets, Bags, . . . ;
- very hard to generate (balanced) instances randomly

Red-black Trees: Summary

- Statistics: 348 test cases were generated
- One error found: crucial violation against red/black-invariants
- Red-black-trees degenerate to linked list
  (insert/search, etc. only in linear time)
- Not found within 12 years
- Reproduced meanwhile by random test tool

Case Studies: Stateless Firewalls (Packet Filters)

Goal:

Test if a packet filter (firewall) configuration conforms to a given policy.

- A packet filter filters (e.g., rejects or denies) packets based on
  - source address destination address
  - protocol
- As usual
  - model firewalls (e.g., networks and protocols) and their policies in HOL
  - use HOL-TestGen for test-case generation

Case Studies: Stateful Firewalls

Goal:

Test if a stateful firewall supports stateful protocols correctly.

- Obvervation:
  - protocols like ftp and VoIP have an internal state
  - and need to be filtered (dynamically) based on their state
- Idea:
  - re-use our state-less model
  - model an observer using a monadic fold construction
  - this observers manages the state at the execution time
  - for many cases, an observer can be generated automatically

Firewall Testing: Summary

- Remark:
  - Stateless firwalls are a **unit testing** scenario
  - Statefull firwalls are a **sequence testing** scenario
- Successful testing if a concrete configuration of a network firewall correctly implements a given policy
- Non-trivial test-case Generation
- Non-trivial state-space (IP Adresses)
- Sequence testing used for stateful firewalls
- Realistic, but amazingly concise model in HOL!

Outline

Conclusion

- Approach based on theorem proving
  - test specifications are written in HOL
  - functional programming, higher-order, pattern matching
- Test hypothesis explicit and controllable by the user (can be seen as proof-obligations)
- Proof-state explosion controllable by the user
- Although logically puristic, systematic unit-test of a “real” compiler library is feasible!
- Verified tool inside a (well-known) theorem prover

Ongoing and Future Work

- Ongoing work includes the development of support for:
  - integration of SAT and SMT Solvers
  - domain-specific test case generation
  - theories for simplifying and transforming test theories
- Future works could include the development for:
  - test theories for three-valued specification (e.g., UML/OCL)
  - integration of unit- and sequence testing approaches
  - ...

Thank you
for your attention!

Any questions or remarks?

The HOL-TestGen can be downloaded from:
`http://www.brucker.ch/projects/hol-testgen/`
(including source, examples, and documentation)

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Part I

Appendix

Further Remarks

- In HOL, Sequence Testing and Unit Testing are the same!

- The **White-box Test** offers potentials to prune unfeasible paths early ... (but no large programs tried so far ...)

Further Remarks

- In HOL, Sequence Testing and Unit Testing are the same!
  TS pattern **Unit Test**:

$$\text{pre}\, x \longrightarrow \text{post}\, x (\mathit{prog}\ x)$$

- The **White-box Test** offers potentials to prune unfeasible paths early ... (but no large programs tried so far ...)

Further Remarks

- In HOL, Sequence Testing and Unit Testing are the same!
  TS pattern **Sequence Test**:

$$\text{accept}\, trace \Longrightarrow P(\text{Mfold}\, trace\ \sigma_0 prog)$$

- The **White-box Test** offers potentials to prune unfeasible paths early ... (but no large programs tried so far ...)

Further Remarks

- In HOL, Sequence Testing and Unit Testing are the same!
  TS pattern **Reactive Sequence Test**:

$$\text{accept } \mathit{trace} \Longrightarrow P(\text{Mfold } \mathit{trace}\ \sigma_0 \\ (\text{observer observer rebind subst } \mathit{prog}))$$

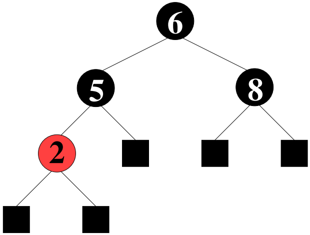
- The **White-box Test** offers potentials to prune unfeasible paths early ... (but no large programs tried so far ...)

Modeling Red-black Trees I

Red-Black Trees:

Red Invariant: each red node has a black parent.

Black Invariant: each path from the root to an empty node (leaf) has the same number of black nodes.



datatype

color = R | B

tree = E | T color (α tree) (β :: ord item) (α tree)

Modeling Red-black Trees II

- Red-Black Trees: Test Theory

consts

$$\begin{array}{lll} \text{redinv} & :: & \text{tree} \Rightarrow \text{bool} \\ \text{blackinv} & :: & \text{tree} \Rightarrow \text{bool} \end{array}$$

recdef blackinv measure (λ t. (size t))

blackinv E = True

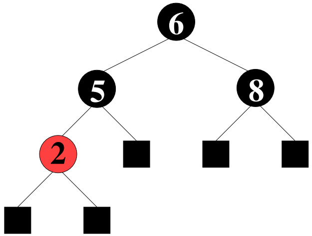
blackinv (T color a y b) =

((blackinv a) $\wedge$ (blackinv b)

$\wedge$ ((max B (height a)) = (max B (height b))))

recdev redinv measure ...

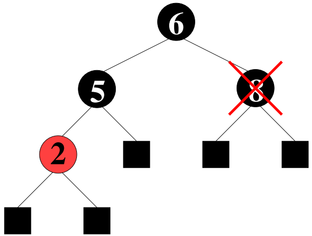
Red-black Trees: sml/NJ Implementation



(a) pre-state

Figure: Test Data for Deleting a Node in a Red-Black Tree

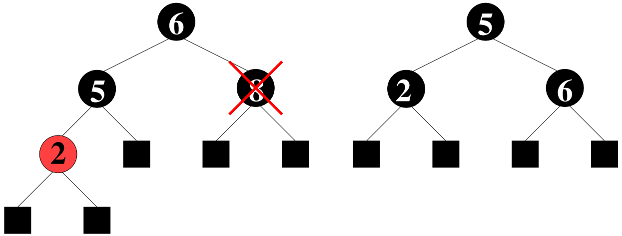
Red-black Trees: sml/NJ Implementation



(b) pre-state: delete "8"

Figure: Test Data for Deleting a Node in a Red-Black Tree

Red-black Trees: sml/NJ Implementation

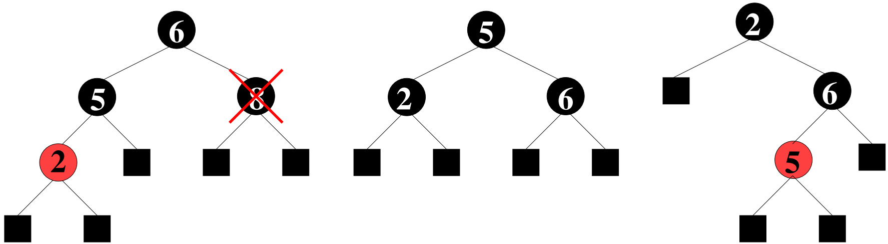


(b) pre-state: delete “8”

(c) correct result

Figure: Test Data for Deleting a Node in a Red-Black Tree

Red-black Trees: sml/NJ Implementation



(b) pre-state: delete "8" (c) correct result (d) result of sml/NJ

Figure: Test Data for Deleting a Node in a Red-Black Tree

Red-black Trees: Test Specification

- Red-Black Trees: Test Specification

  test_spec :
  $$\text{"isord } t \wedge \text{redinv } t \wedge \text{blackinv } t \wedge \text{isin } (y :: \text{int}) \; t \longrightarrow (\text{blackinv}(\text{prog}(y, t)))\text{"}$$

  where prog is the program under test (e.g., delete).

- Using the standard-workflows results, among others:

  $$\text{RSF} \longrightarrow \text{blackinv } (\text{prog } (100, \; T \; B \; E \; 7 \; E))$$
  $$\text{blackinv } (\text{prog } (-91, \; T \; B \; (T \; R \; E \; -91 \; E) \; 5 \; E))$$

The State-less Firewall Model I

First, we model a packet:

types (α,β) packet = "id × protocol × α src × α dest × β conten

where

id: a unique packet identifier, e.g., of type Integer

protocol: the protocol, modeled using an enumeration type (e.g., ftp, http, smtp)

α src (α dest): source (destination) address, e.g., using IPv4:

types
ipv4_ip = "(int × int × int × int)"
ipv4 = "(ipv4_ip × int)"

β content: content of a packet

The State-less Firewall Model II

- A **firewall** (packet filter) either accepts or denies a packet:

  datatype
  α out = accept α | deny

- A **policy** is a map from `packet` to `packet out`:

  types
  (α, β) Policy = "(α, β) packet $\rightharpoonup$ $((\alpha, \beta)$ packet$)$ out"

- Writing policies is supported by a specialised combinator set

State-full Firewalls: An Example (ftp)

- based on our state-less model:
  Idea: a firewall (and policy) has an internal state:
- the firewall state is based on the history and the current policy:

  types (α,β,γ) FWState = "$\alpha \times (\beta,\gamma)$ Policy"

- where FWStateTransition maps an incoming packet to a new state

  types (α,β,γ) FWStateTransition =
  "$((\beta,\gamma)$ In_Packet $\times$ (α,β,γ) FWState) $\rightharpoonup$
  $((\alpha,\beta,\gamma)$ FWState)"