Parametric Log Checking

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Formal methods

“Program testing can be used to show the presence of bugs, but never to show their absence.” – Edsger Dijkstra

• Formal methods = rigorous mathematical techniques used to specify, develop, and verify systems.
  • Formal specification
  • Formal verification
Static vs. dynamic analysis

• Static analysis
  - State space exploration
  - Abstract interpretation
  - Q: Does SW (resp. its model) meet its specification?
    - (under specific conditions)

• Dynamic analysis
  - Experimental evaluation
  - Trace analysis
  - Q: Did we witness a bug?
    - (in a set of runs)
Software testing vs. Runtime verification

• "Classical" SW testing:
  • (1) Setup, (2) Exercise, (3) Verify, (4) Teardown (shared fixture strategies...)
  • Systematic/random (coverage driven, fuzz-testing, ...)
• Q1: What to test next?
• Q2: Is it enough?

<table>
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<tr>
<th>Setup</th>
<th>Exercise</th>
<th>Verify</th>
</tr>
</thead>
<tbody>
<tr>
<td>env1</td>
<td>input1</td>
<td>assert1</td>
</tr>
<tr>
<td>env1</td>
<td>input2</td>
<td>assert2</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
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</tbody>
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Software testing vs. Runtime verification

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<tr>
<td>env1</td>
<td>input1</td>
<td>assert1 = expect(input1)</td>
</tr>
<tr>
<td>env1</td>
<td>input2</td>
<td>assert2 = expect(input2)</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

```
// setup
Jarvis.reset_scheduler()
cart = Cart(2, 50, 0)
c = CartCtl(cart, Jarvis)
// exercise
item = CargoReq('A', 'B', 20, 'helmet')
Jarvis.plan(0, add_load, (c, item))
Jarvis.run()
// verify
self.assertEqual(cart.pos, 'B')
self.assertTrue(cart.empty())
self.assertEqual(Status.Idle, c.status)
self.assertEqual(helmet.context, 'unloaded')
```
Software testing vs. Runtime verification

• "Not so Classical" SW testing:
  • (1) Setup, (2) Exercise, (3) Verify, (4) Teardown (shared fixture strategies...)
  • Systematic/random (coverage driven, fuzz-testing, ...)
  • Q1: What to test next?
  • Q2: Is it enough?

<table>
<thead>
<tr>
<th>Test input</th>
<th>Exp. output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup</td>
<td>Exercise</td>
</tr>
<tr>
<td>env1</td>
<td>input1</td>
</tr>
<tr>
<td>env1</td>
<td>input2</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Software testing vs. Runtime verification (assert) part

- Fully automated test:
  - Bug-hunting ultimate Q: Under which condition the system behaves incorrectly?
  - Problem1: How to generate inputs? (cover test items, fuzz)
  - Problem2: Who provides me with the expect() function?

### Setup | Exercise | Verify
---|---|---
env1 | input1 | assert1 = expect(input1)
env1 | input2 | assert2 = expect(input2)
... | ... | ...

```python
Jarvis.reset_scheduler()
cart = Cart(2, 50, 0)
c = CartCtl(cart, Jarvis)
while 42:
    test_inp = generate_test_input()
Jarvis.run()
// verify
assert(expect(test_input))
```
Runtime verification – expect() function?

• There isn’t “someone”. There’s just you. 😞

• Where does it come from?
  • From the SUT documentation & specification…

• Except when you are working on high critical-level app, there is no such thing as precise documentation. 😞😞

• Gap between developers and RV/FM practitioners:
  • How to easily write formal specification.

• Moreover, we don’t want “expect” to represent just a set of post-conditions, rather:

• Properties representing expected sequence of events in the SUT.
  
  Example: []( request(d) → <> response(d))
Runtime verification – properties

• Used different formalisms:
  • extended regular expressions,
  • state machines,
  • context-free grammar,
  • PSL, LTL, ptLTL, MTL, …

• How to monitor liveness?
  • Liveness is important for potentially endless programs.
  • RV cannot notify about violation of liveness during execution → We cannot decide if the system will eventually be back into an expected state. Two possible workarounds:
    • System must react in a specific time limit (add & check “heartbeat” in the system).
    • PSL extension with non true/false verdicts: Risk and Pending (all future obligations are/are not fulfilled).
• Specification of SUT is synthesized to runtime monitors.
• SUT to exhibits sequence of events.
• Runtime monitors (or so called dynamic analysers) checks whether the next occurrence of an event is acceptable wrt. specification.
• Type of events? Who will provide them? Probe (code) injection.
• Inline vs. Outline analysers (monitor + probes as one or isolated)
• Online vs. Offline (runtime monitor vs. post-mortem analysis)
Runtime verification – instrumentation

• Code injection (probes and/or monitors) techniques:
  • Changing (adding/decorating) source code.
  • Instrumenting while compiling (a special compiler adds the code to join points).
  • Changing the binary when the program is loaded into the memory.
  • Using a code interceptors at runtime.

• Or, separate program communicating with SUT.
  • tracers,
  • log monitors, or even
  • profilers.
Runtime verification vs. runtime monitoring

• RV: Q: Does it behave correctly under different conditions (even unknown in advance)?
  • i.e. “I will give you inputs, you will provide me with pass/fail.”

• RM: Target: production system
  • Test environment + Test input generator → Real environment + Real input
  • Potentially endless programs:
    • Services, control systems, sensing systems

• Q: Does it still behave correctly?
• If not, possible actions based on criticality level of the problem:
  • Notify.
  • Switch to partial-operational or safe-mode.
  • Restart (+ self healing).
  • Mission fail.
Log checking

- No code change – separate program,
- Outline RV – SUT generates event in logs, log checker reads it,
- Online/Offline RV – can analyse log as a stream,
- Most importantly, aim at easy specification:
  - Every developer should be able to specify property.
Log checking – property specification

• Good vs. bad properties = expected or unexpected event sequences

• Good property:
  • Once the first event occurs, the whole sequence must occur.
  • Example: If a datastore is opened, then possibly accessed, it must be closed.
    • “Open Use* Close”
  • Note: Violation can be witnessed at the end of the trace.

• Bad property:
  • If a sequence of events is witnessed, report the violation.
  • Example: Every response to a request to the store must be of status 200.
    • “RequestStore StatusOtherThan200”
Log checking – example httpd reload

bad_property:
FailedReload: “HttpdReload HttpdFailed”
FailedReload2: “HttpdReload HttpdConfigured! HttpdFailed”

events:
HttpdReload: “.* systemd\[1\]: Reloading The Apache HTTP Server.”
HttpdFailed: “.* systemd\[1\]: Reload failed for The Apache HTTP Server.”
HttpdConfigured: “.* httpd\\[\d+\\]: Server configured, listening on: .*”

Aug 14 12:03:37 systemd[1]: Reloading The Apache HTTP Server.
Aug 14 12:03:37 httpd[3296577]: AH00526: Syntax error on line 1 of /etc/httpd/conf/httpd.conf:
Aug 14 12:03:37 httpd[3296577]: Invalid command 'asdf', perhaps misspelled or defined by a module not included in the server configuration
Aug 14 12:03:37 systemd[1]: httpd.service: Control process exited, code=exited, status=1/FAILURE
Log checking – how does it work?

Properties
specification.yml

Event
events

Automata
generator

Constraints
Parsing

Events
ERE

Automata
template

Filter

Monitor

Automata
Instances

Report

Log
Bad property 'HttpdReload HttpdConfigured! HttpdFailed' with id 'FailedReload2' was violated!

Sequence of events that caused the violation:
   event id = HttpdReload
   event id = HttpdFailed

Aug 14 12:03:37 systemd[1]: Reloading The Apache HTTP Server.
Aug 14 12:03:37 httpd[3296577]: AH00526: Syntax error on line 1 of /etc/httpd/conf/httpd.conf:
Aug 14 12:03:37 httpd[3296577]: Invalid command 'asdf', perhaps misspelled or defined by a module not included in the server configuration
Aug 14 12:03:37 systemd[1]: httpd.service: Control process exited, code=exited, status=1/FAILURE
• Consider property: “Open Use* Close”
  • “Every file which is opened, then used, must be eventually closed.”
• The trace of events with multiple violations:
  • \[\text{Open}(f_1) \text{ Use}(f_1) \text{ Use}(f_1) \text{ Open}(f_2) \text{ Use}(f_2) \text{ Close}(f_1) \text{ Use}(f_2)\]

• We need to take into account parameters \(\rightarrow\) Parametrised sequences: “Open(f) Use(f)* Close(f)”
• Events in a parametrised sequence share parameter values:
  • \(f_1:\ \text{Open}(f_1) \text{ Use}(f_1) \text{ Use}(f_1) \text{ Open}(f_2) \text{ Use}(f_2) \text{ Close}(f_1) \text{ Use}(f_2)\)
  • \(f_2:\ \text{Open}(f_1) \text{ Use}(f_1) \text{ Use}(f_1) \text{ Open}(f_2) \text{ Use}(f_2) \text{ Close}(f_1) \text{ Use}(f_2)\)
Log checking – more parameters

• Parameterised sequence can have more parameters:
  • Bad_property: “Create(c, i) Next(i)* Update(c) Next(i)”
  • Once an iterator over collection is created, it must not be used after collection update.

bad_property:
  UnsafeIter: “Create Next* Update Next”

events:
  Create: “%{WORD:col}.begin = %{WORD:it}”
  Next: “%{WORD:it}.next”
  Update: “%{WORD:col}.(remove|add|clear)”

constraints:
  - “Create.col = Update.col”
  - “Create.it = Next.it”
Log checking – example sshd

bad_properties:
  BFAttack: "F1 F2+ F3"

events:
  F1: "%{DATE_ISO8601:ts} .* sshd: Failed password for invalid user %{WORD:user} from %{IP:ip}"
  F2: "%{DATE_ISO8601:ts} .* sshd: Failed password for invalid user %{WORD:user} from %{IP:ip}"
  F3: "%{DATE_ISO8601:ts} .* sshd: Failed password for invalid user %{WORD:user} from %{IP:ip}"

constraints:
  - "F3.ts - F1.ts <= 0h0m10s"
  - "F1.ts < F3.ts"
  - "F1.ip = F2.ip"
  - "F2.ip = F3.ip"

2022-09-15 05:43:10 wee sshd: Failed password for invalid user root from 61.177.173.10
2022-09-15 05:43:12 wee sshd: Failed password for invalid user root from 92.255.85.70
2022-09-15 05:43:23 wee sshd: Failed password for invalid user root from 61.177.173.10
2022-09-15 05:43:24 wee sshd: Failed password for invalid user mpb from 39.109.113.139
2022-09-15 05:43:25 wee sshd: Failed password for invalid user root from 61.177.173.10
2022-09-15 05:43:27 wee sshd: Failed password for invalid user root from 61.177.173.10
2022-09-15 05:43:37 wee sshd: Failed password for invalid user tomcat from 193.106.191.157
Log checking – parameters, how does it work?

1. **Properties**
   - Specification.yml

2. **Event extraction**

3. **Automata generator**

4. **Constraints parsing**

5. **Constraints**

6. **Automata template**

7. **Events ERE**

8. **Filter**

9. **Monitor**

10. **Automata instances**

11. **Report**

12. **Log**
Log checking – parameters, how does it work?

**Property:** foo(o) bar(o,p) baz(p)  

**FA template:**

<table>
<thead>
<tr>
<th>Line</th>
<th>Trace</th>
<th>o=1</th>
<th>o=2</th>
<th>p=a</th>
<th>q=b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>foo(1)</td>
<td>q1[1/o]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>bar(1,a)</td>
<td></td>
<td></td>
<td></td>
<td>q2[a/p]</td>
</tr>
<tr>
<td>3</td>
<td>foo(2)</td>
<td></td>
<td>q1[2/o]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>bar(1,b)</td>
<td></td>
<td></td>
<td>q2[b/p]</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>bar(2,b)</td>
<td></td>
<td></td>
<td>q2[b/p]</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>baz(b)</td>
<td></td>
<td></td>
<td></td>
<td>q3[b/q]</td>
</tr>
<tr>
<td>7</td>
<td>foo(1)</td>
<td>q1[1/o]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Plogchecker

- Prototype tool (v2.0), implemented in Golang:
  plogchecker [-p prop.yml] [-l logfile] [-s JSON|TEXT]
- Example: $ journalctl | plogchecker -l sshdprop.yml -s JSON
- Automata + parameters:
  - Every specified event has a collection of seen parameter values of the event.
  - Parameter values (collection items) reference to other collections (their predecessors in the sequence).
  - Once reached final event, the whole sequence is erased and possibly reported.
- Inefficient: More unique values or their combinations in the log mean more memory consumption.
  - Different approaches to store the parameters or to represent automata.
- Garbage collector:
  - Safe = all seen values are preserved (too consuming), only closed seqs. are cleared.
  - Unsafe = we may miss some faults, but it can still provide useful feedback.
Plogchecker – example RemoteStation-Car

<table>
<thead>
<tr>
<th>Timestamp, RS name, ID, Event type, Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1614582126860, Roboauto-RS-NLR-E01, 0, RSEVENT, connectedToGateway</td>
</tr>
<tr>
<td>1614582147614, Roboauto-RS-NLR-E01, 1, RSEVENT, connectingToVehicle</td>
</tr>
<tr>
<td>1614582148114, Roboauto-RS-NLR-E01, 49, RSCOMMAND, ReadyAck</td>
</tr>
<tr>
<td>1614582187719, Roboauto-RS-NLR-E01, 75434, RSCOMMAND, DriveAck</td>
</tr>
<tr>
<td>1614582220730, Roboauto-RS-NLR-E01, 75435, RSEVENT, drivingVehicle</td>
</tr>
<tr>
<td>1614582228730, Roboauto-RS-NLR-E01, 143104, RSCOMMAND, PauseAck</td>
</tr>
<tr>
<td>1614582228730, Roboauto-RS-NLR-E01, 143105, RSEVENT, connectedToVehicle</td>
</tr>
<tr>
<td>1614582240705, Roboauto-RS-NLR-E01, 149780, RSCOMMAND, DriveAck</td>
</tr>
<tr>
<td>1614582240705, Roboauto-RS-NLR-E01, 149781, RSEVENT, drivingVehicle</td>
</tr>
<tr>
<td>1614582238584, Roboauto-RS-NLR-E01, 179557, RSCOMMAND, PauseAck</td>
</tr>
<tr>
<td>1614582238584, Roboauto-RS-NLR-E01, 179558, RSEVENT, connectedToVehicle</td>
</tr>
</tbody>
</table>

$ plogchecker -p UC2_RS_cmds.yml -l lab_robot.csv

```json
{
  "properties": {
    "rs_pause": {
      "property": "P D E F",
      "violated": [
      ...
    
    "events_sequence": [
      "event_id": "P",
      "log_file": "lab_robot.csv",
      "log_lineno": 143106,
      "log_line": "1614582220730,Roboauto-RS-NLR-E01,143104,RSCOMMAND,PauseAck"
    }...
  
  
  # connection established...drivingVehicle
  rs_conn: "A B O* C O* D O* E O* F O*"

  # pause in the middle and continue
  rs_pause: "P D E F"

  # close connection, odometry receive possible
  rs_end: "F O* R"
```
Plogchecker – example Open-Shadow

```plaintext
execve("/bin/grep", ["grep", "^root:", "/etc/shadow"], 0x7fffffd6b9c30, /* 14 vars */ ) = 0
arch_prctl(Arch_SET_FS, 0x7f667f70ab48) = 0
mprotect(0x7f667f707000, 4096, PROT_READ) = 0
mprotect(0x55a28597e000, 16384, PROT_READ) = 0
getuid() = 0
open("/etc/shadow", O_RDONLY|O_LARGEFILE) = 3
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f667f673000
read(3, "root:!::0:::::\nbin:...", 1024) = 448
mmap(NULL, 16384, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f667f66f000
munmap(0x7f667f66f000, 16384) = 0
ioctl(1, TIOCGWINsz, {ws_row=52, ws_col=94, ws_xpixel=0, ws_ypixel=0}) = 0
writev(1, [{iov_base="root:!::0:::::\nbin:...", iov_len=14}, {iov_base="\n", iov_len=1}], 2) = 15
read(3, "", 1024) = 0
close(3) = 0
munmap(0x7f667f673000, 4096) = 0
```

shadow.yml

```
bad_properties:
  shadow: "O R"
```

**Specification**

```plaintext
LOG

$ strace ... | plogchecker -p shadow.yml -s TEXT
Bad property 'O R' with id 'shadow' was violated!
Sequence of events that caused the violation:
  7. openat("/etc/shadow", O_RDONLY|O_LARGEFILE) = 3
event id = 0
  10. read(3, "root:!::0:::::\nbin:...", 1024) = 448
event id = R
```
Conclusion

• Runtime verification improves your software testing.
• Runtime verification complements formal verification when:
  • it is computationally impossible to exhaustively verify,
  • it is too expensive/time consuming (missing well-suited tools/skills),
  • model assumptions do not meet the real system.
• Log checking:
  • relatively easy to specify properties,
  • possible wide acceptance (almost all systems log their events),
  • enables post-mortem/offline analysis,
  • can be used in production environment.
• Still much work to make it universal, e.g.:
  • efficient garbage collector for parametrised instances,
  • high throughput + low overhead: currently 2.7k lines/sec (Ryzen7), >30MB worst case
  • more data types (e.g. json),
  • multi-line log events,
  • other than text logs.
More on Runtime verification

• Runtime Verification conference: https://runtime-verification.github.io/


  • Runtime Verification – The Linux Kernel Documentation (2022-07-29)
Verification and Validation of Automated Systems’ Safety and Security

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