Parametric Log Checking

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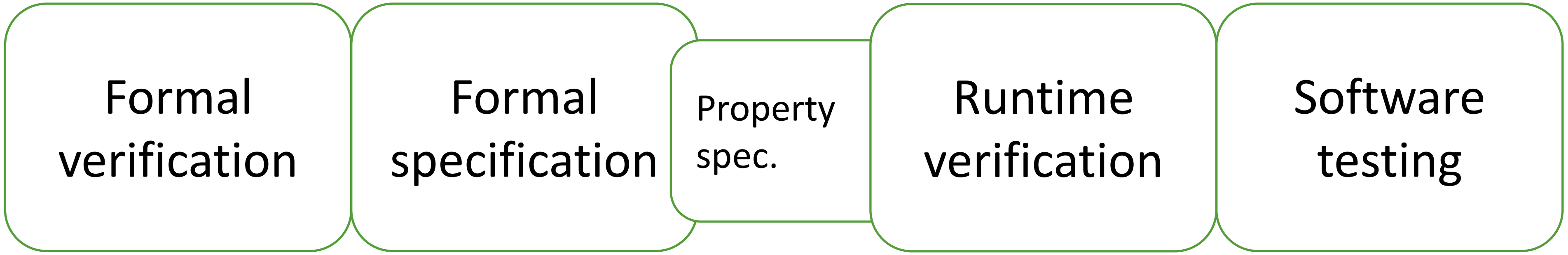
Formal methods

“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
- Dynamic analysis



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

- 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?

Test input ← | → Exp. output

Setup	Exercise	Verify
env1	input1	assert1
env1	input2	assert2
…	…	…

```
// 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

- ”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?

Test input ← | → Exp. output

Setup	Exercise	Verify
env1	input1	assert1 = expect(input1)
env1	input2	assert2 = expect(input2)
…	…	…

```
// 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')
```

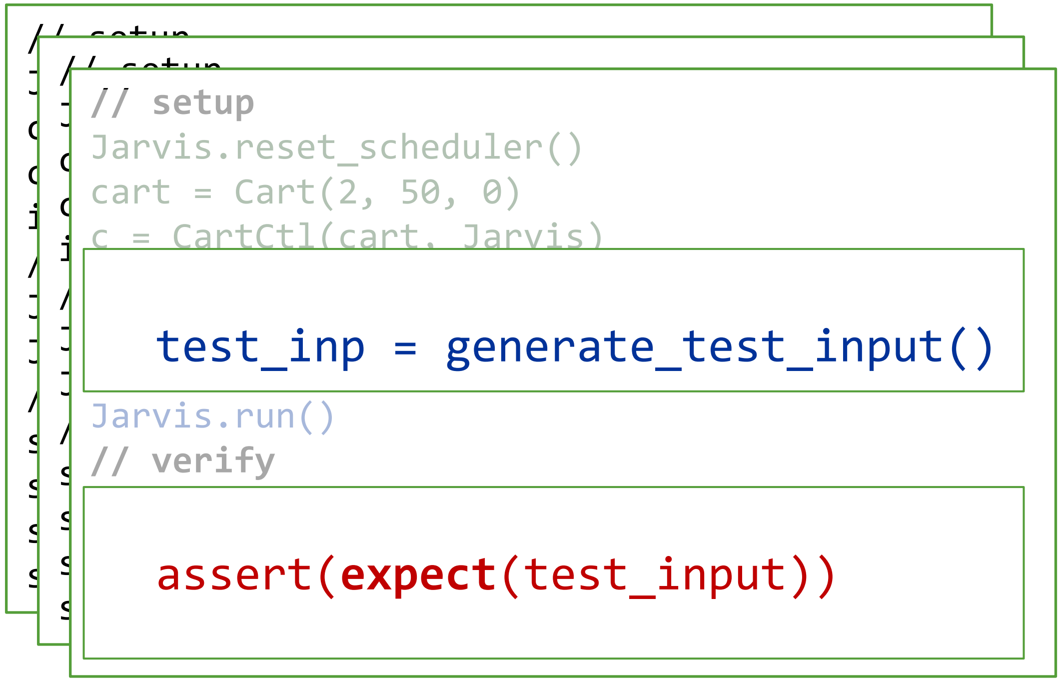
Software testing vs. Runtime verification

- ”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?

Test input ← | → Exp. output

Setup	Exercise	Verify
env1	input1	assert1 = expect(input1)
env1	input2	assert2 = expect(input2)
…	…	…



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?

Test input ← | → Exp. output

Setup	Exercise	Verify
env1	input1	assert1 = expect(input1)
env1	input2	assert2 = expect(input2)
…	…	…

```
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?

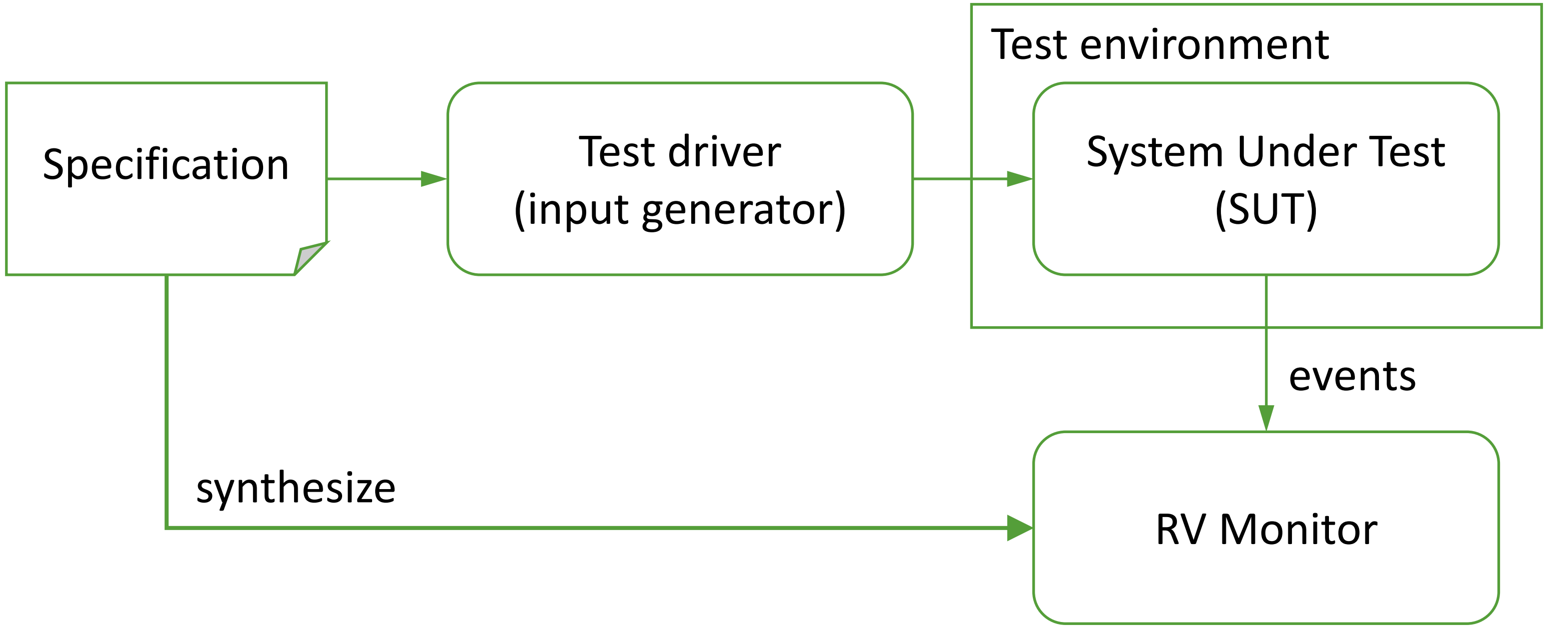
- There isn't "someone". There's just you. ☹
- Where does it come from?
  - From the SUT documentation & specification…
- Except when you are working on high critical-level app, there is no such thing as precise documentation. ☹☹
- Gap between developers and RV/FM practitioners:
  - How to easily write 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: $[](\, request(d) \rightarrow \langle\rangle\, response(d))$

Runtime verification – properties

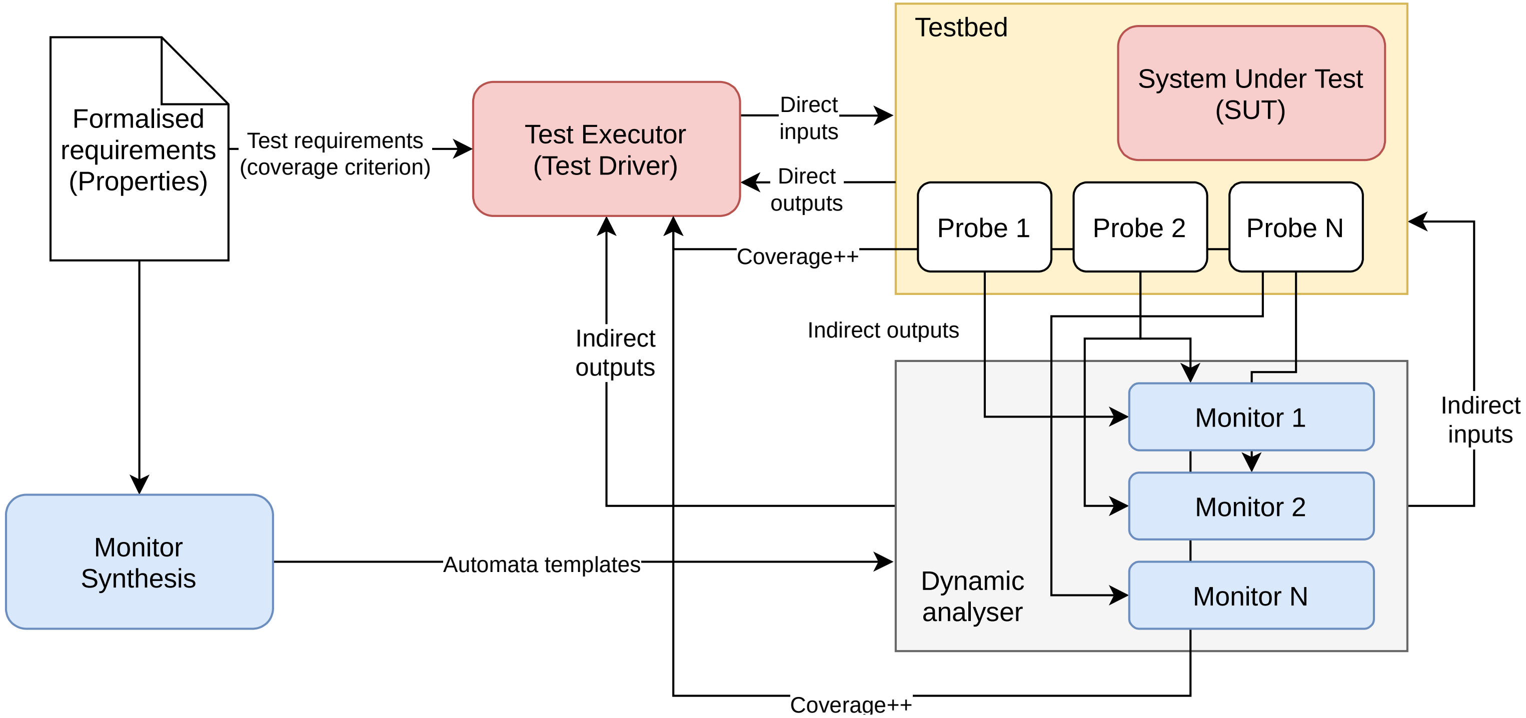
- Used different formalisms:
  - extended regular expressions,
  - state machines,
  - context-free grammar,
  - PSL, LTL, ptLTL, MTL, …
- How to monitor liveness?
  - Liveness is important for potentially endless programs.
  - RV cannot notify about violation of liveness during execution → We cannot 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).

Runtime verification – architecture



- 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.

Runtime verification – classification



- 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.

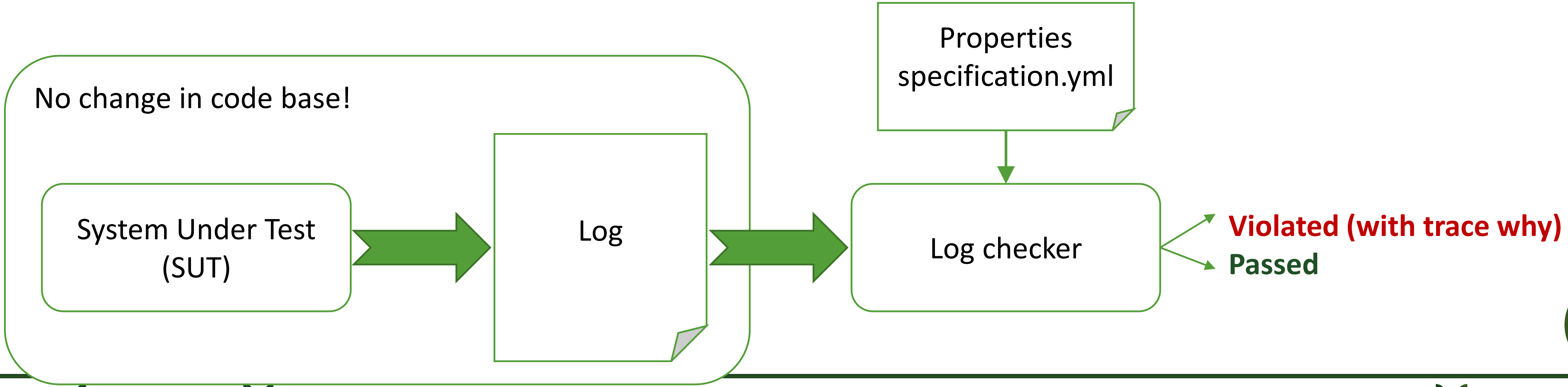
Runtime verification vs. runtime monitoring

- 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, sensoring 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

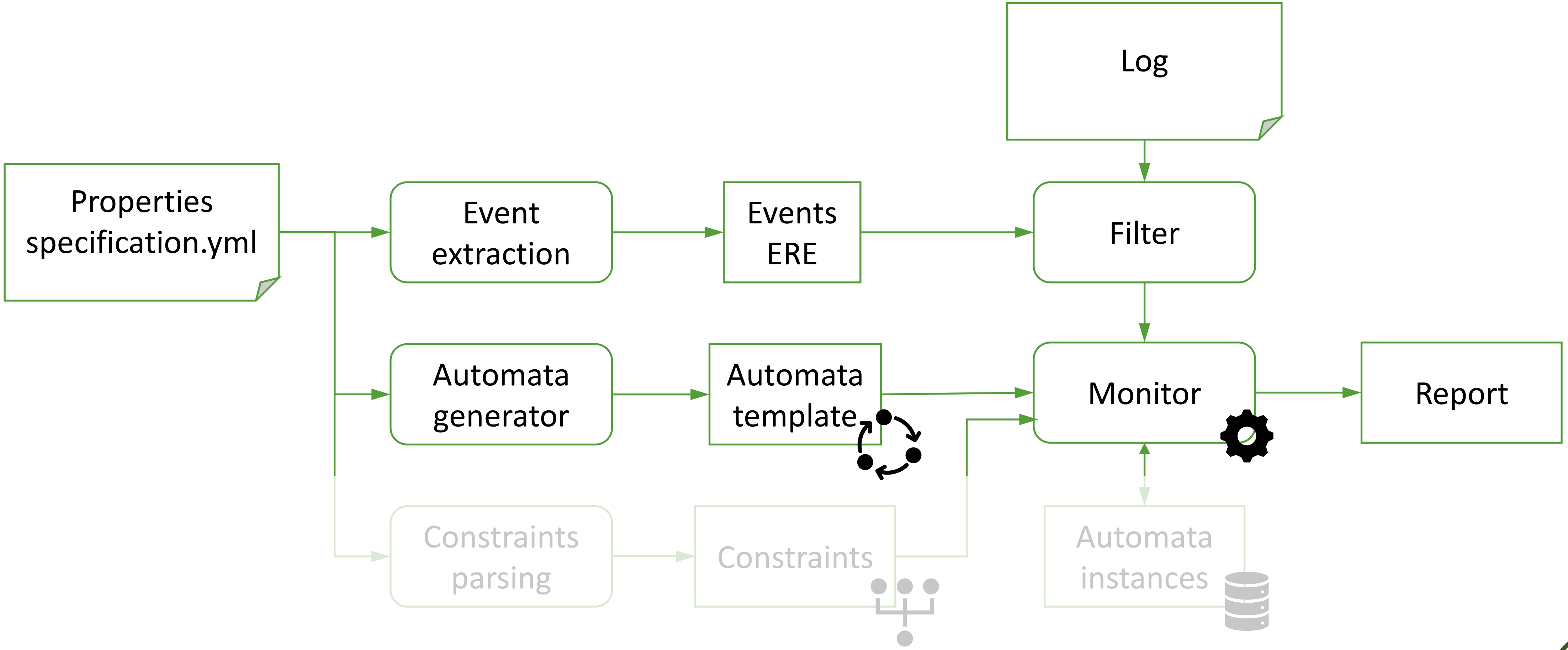
- Good vs. bad properties = expected or unexpected event sequences
- Good property:
  - Once the first event occurs, the whole sequence must occur.
  - Example: If a datastorage is opened, then possibly accessed, it must be closed.
    - “Open Use* Close”
  - Note: Violation can be witnessed at the end 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
Aug 14 12:03:37 systemd[1]: Reload failed for The Apache HTTP Server.
```

Log checking – how does it work?



Log checking – example httpd reload

```
Bad property 'HttpdReload HttpdConfigured! HttpdFailed' with id
'FailedReload2' was violated!
    Sequence of events that caused the violation:
      1. Aug …systemd[1]: Reloading The Apache HTTP Server.
        event id = HttpdReload
      5. Aug …systemd[1]: Reload failed for The Apache HTTP Server.
        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:
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Aug 14 12:03:37 systemd[1]: httpd.service: Control process exited,
code=exited, status=1/FAILURE
Aug 14 12:03:37 systemd[1]: Reload failed for The Apache HTTP Server.
```

Log checking – parameters

- Consider property: “Open Use* Close”
  - “Every file which is opened, then used, must be eventually closed.”
- The trace of events with multiple violations:
  - Open(f1) Use(f1) Use(f1) Open(f2) Use(f2) Close(f1) Use(f2)
- We need to take into account parameters → Parametrised sequences: “Open(f) Use(f)* Close(f)”
- Events in a parametrised sequence share parameter values:
  - f1: Open(f1) Use(f1) Use(f1) Open(f2) Use(f2) Close(f1) Use(f2)
  - f2: Open(f1) Use(f1) Use(f1) Open(f2) Use(f2) Close(f1) Use(f2)

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

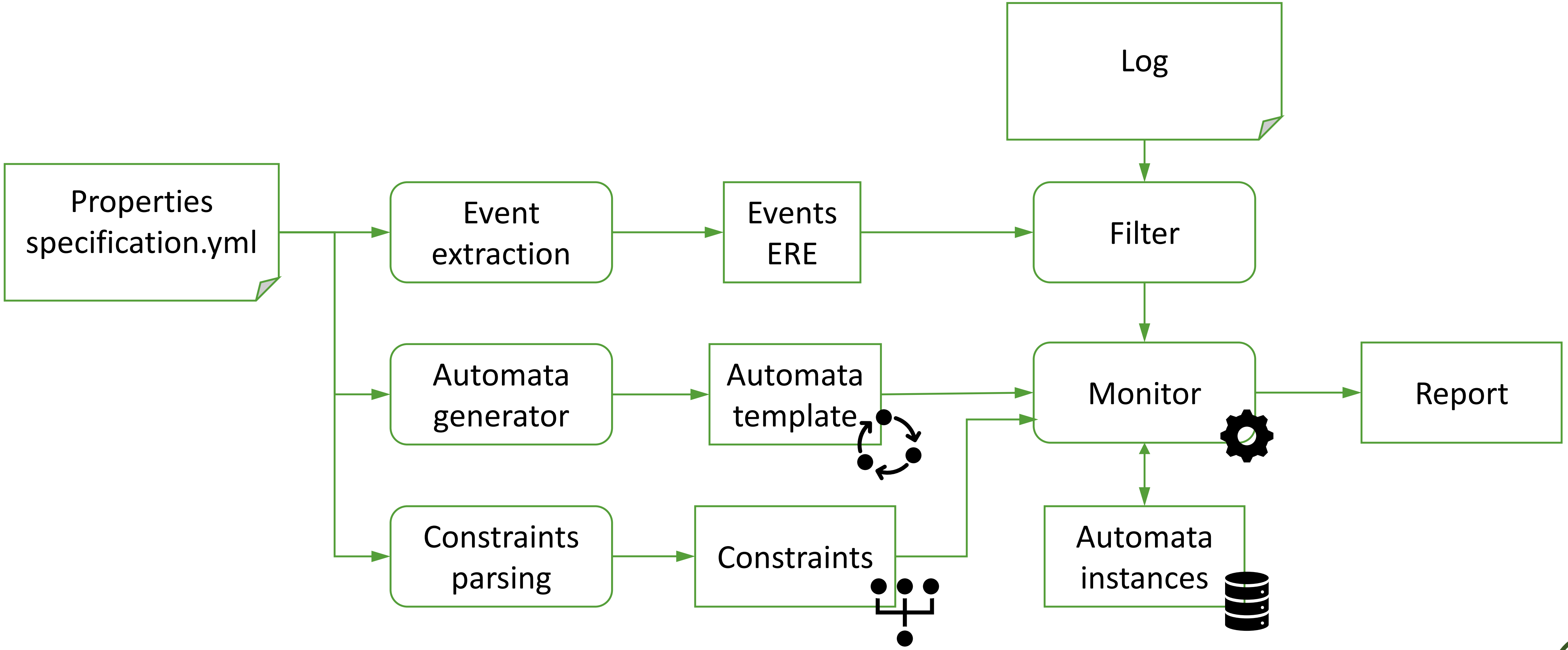
```
bad_properties:
  BFAttack: "F1 F2+ F3"

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"
```

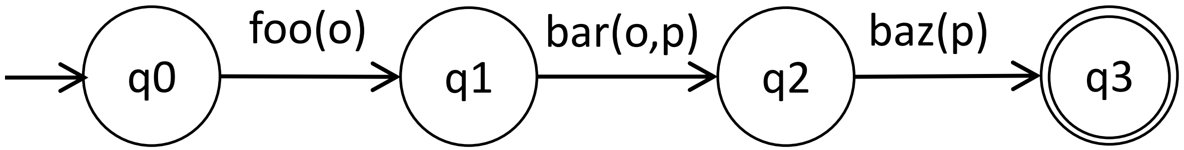
```
2022-09-15 05:43:10 wee sshd: Failed password for invalid user root from 61.177.173.10
2022-09-15 05:43:12 wee sshd: Failed password for invalid user root from 92.255.85.70
2022-09-15 05:43:23 wee sshd: Failed password for invalid user root from 61.177.173.10
2022-09-15 05:43:24 wee sshd: Failed 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?



Log checking – parameters, how does it work?

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



Line	Trace	o=1	o=2	p=a	q=b
1	foo(1)	q1[1/o]			
2	bar(1,a)			q2[a/p]	
3	foo(2)		q1[2/o]		
4	bar(1,b)			q2[b/p]	
5	bar(2,b)			q2[b/p]	
6	baz(b)				q3[b/q]
7	foo(1)	q1[1/o]			

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

```
Timestamp,RS name,ID,Event type,Data
1614582126860,Roboauto-RS-NLR-E01,0,RSEVENT,connectedToGateway
1614582147614,Roboauto-RS-NLR-E01,1,RSEVENT,connectingToVehicle
1614582148114,Roboauto-RS-NLR-E01,49,RSCOMMAND,ReadyAck
1614582148114,Roboauto-RS-NLR-E01,50,RSEVENT,connectedToVehicle
1614582187719,Roboauto-RS-NLR-E01,75434,RSCOMMAND,DriveAck
1614582187719,Roboauto-RS-NLR-E01,75435,RSEVENT,drivingVehicle
1614582220730,Roboauto-RS-NLR-E01,143104,RSCOMMAND,PauseAck
1614582220730,Roboauto-RS-NLR-E01,143105,RSEVENT,connectedToVehicle
1614582224075,Roboauto-RS-NLR-E01,149700,RSCOMMAND,DriveAck
1614582224075,Roboauto-RS-NLR-E01,149701,RSEVENT,drivingVehicle
1614582238584,Roboauto-RS-NLR-E01,179557,RSCOMMAND,PauseAck
1614582238584,Roboauto-RS-NLR-E01,179558,RSEVENT,connectedToVehicle
```

```
$ plogchecker -p UC2_RS_cmds.yml -l lab_robot.csv
{
  "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"
} ...
```

```
properties:

    # 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”

events:
    A: .*RSEVENT,connectedToGateway
    B: .*RSEVENT,connectingToVehicle
    C: .*RSCOMMAND,ReadyAck
    D: .*RSEVENT,connectedToVehicle
    E: .*RSCOMMAND,DriveAck
    F: .*RSEVENT,drivingVehicle
    O: .*RSODOMETRY,
    P: .*RSCOMMAND,PauseAck
    R: .*RSCOMMAND,Release
```

Plogchecker – example Open-Shadow

1

SUT

```
strace  grep ^root: /etc/shadow
```

LOG

2

```
execve("/bin/grep", ["grep", "^root:",
"/etc/shadow"], 0x7ffffd6b9c30, /* 14 vars */ ) = 0
arch_prctl(ARCH_SET_FS, 0x7f667f70ab48) = 0
set_tid_address(0x7f667f70af90)         = 138
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:::::", iov_len=14},
{iov_base="\n", iov_len=1}], 2) = 15
read(3, "", 1024)                       = 0
close(3)                                = 0
munmap(0x7f667f673000, 4096)            = 0
```

shadow.yml

Specification

3

```
bad_properties:
  shadow: "O R"
events:
  O: 'open(at)?\("/etc/shadow",.* = %{NUMBER:fd}$'
  R: 'read\(%{NUMBER:fd},.* = %{NUMBER:bytes}$'
constraints:
  - "O.fd >= 0"
  - "O.fd = R.fd"
  - "R.bytes > 0"
```

4

```
$ 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 = O
 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/
- D. Jin, M. Dennis, and G.G. Rosu, "Garbage collection for monitoring parametric properties", 2011. doi: 10.1.1.360.5666
- D. Jin, P. O. Meredith, C. Lee and G. Roşu, "JavaMOP: Efficient parametric runtime monitoring framework," *ICSE* 2012, pp. 1427-1430, doi: 10.1109/ICSE.2012.6227231.
- Chen, Z., Wang, Z., Zhu, Y., Xi, H., Yang, Z. (2016). "Parametric Runtime Verification of C Programs". In: Chechik, M., Raskin, JF. (eds) Tools and Algorithms for the Construction and Analysis of Systems. TACAS 2016. LNCS 9636. Springer. doi: 10.1007/978-3-662-49674-9_17 .
- Zhe Chen, Parametric runtime verification is NP-complete and coNP-complete, Information Processing Letters, Volume 123, 2017, Pages 14-20, ISSN 0020-0190, doi: 10.1016/j.ipl.2017.02.006.
- de Oliveira, D.B., Cucinotta, T., de Oliveira, R.S. (2019). Efficient Formal Verification for the Linux Kernel. In: Ölveczky, P., Salaün, G. (eds) Software Engineering and Formal Methods. SEFM 2019. Lecture Notes in Computer Science(), vol 11724. Springer, Cham. doi: 10.1007/978-3-030-30446-1_17
  - Runtime Verification – The Linux Kernel Documentation (2022-07-29)
  - https://kernel.org/doc/html/latest//trace/rv/runtime-verification.html

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VALU3S

Verification and Validation of Automated Systems' Safety and Security

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