# Two Testing Tools for the Erlang Ecosystem

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# PropEr – proper.softlab.ntua.gr

# PropEr: A property-based testing tool

- Inspired by QuickCheck.
- Open source.
- Has support for
  - Writing properties and test case generators
    `?FORALL/3, ?IMPLIES, ?SUCHTHAT/3, ?SHRINK/2, ?LAZY/1, ?WHENFAIL/2, ?LET/3, ?SIZED/2, aggregate/2, choose2, oneof/1, ...`
  - Stateful (aka "statem" and "fsm") testing.
- Fully integrated with types and specs
  - Generators often come for free!
- Extensions for **targeted** property-based testing.

# Demo program

```
%% A sorting program, inspired by QuickSort
-module(demo).
-export([sort/1]).

-spec sort([T]) -> [T].
sort([]) -> [];
sort([P|Xs]) ->
  sort([X || X <- Xs, X < P])
    ++ [P] ++ sort([X || X <- Xs, P < X]).
```

```
Eshell V9.2.1 (abort with ^G)
1> demo:sort([]).
[]
2> demo:sort([17,42]).
[17,42]
3> demo:sort([42,17]).
[17,42]
4> demo:sort([3,1,2]).
[1,2,3]
```

# A property for the demo program

```
-module(demo).
-export([sort/1]).

-include_lib("proper/include/proper.hrl").

-spec sort([T]) -> [T].
sort([]) -> [];
sort([P|Xs]) ->
  sort([X || X <- Xs, X < P])
    ++ [P] ++ sort([X || X <- Xs, P < X]).

prop_ordered() ->
  ?FORALL(L, list(integer()), ordered(sort(L))).

ordered([]) -> true;
ordered([_]) -> true;
ordered([A,B|T]) -> A =< B andalso ordered([B|T]).
```

generator

# Testing the ordered property

```
$ erl -pa /path/to/proper/ebin
Erlang/OTP 20 [erts-9.2.1] [...] ...

Eshell V9.2.1 (abort with ^G)
1> c(demo).
{ok,demo}
2> proper:quickcheck(demo:prop_ordered()).
.......... 100 dots ..........
OK: Passed 100 tests
true
3> proper:quickcheck(demo:prop_ordered(), 4711).
.......... 4711 dots ..........
OK: Passed 4711 tests
true
```

Runs any number of “random” tests we feel like.

If all tests satisfy the property, the test passes.

# Another property for the program

```
-module(demo).
-export([sort/1]).

-include_lib("proper/include/proper.hrl").

-spec sort([T]) -> [T].
sort([]) -> [];
sort([P|Xs]) ->
  sort([X || X <- Xs, X < P])
    ++ [P] ++ sort([X || X <- Xs, P < X]).

prop_ordered() ->
  ?FORALL(L, list(integer()), ordered(sort(L))).

prop_same_length() ->
  ?FORALL(L, list(integer()),
          length(L) =:= length(sort(L))).

ordered([]) -> ...
```

# Testing the same_length property

```
4> c(demo).
{ok,demo}
5> proper:quickcheck(demo:prop_same_length()).
..............!
Failed: After 14 test(s).
[1,3,-3,10,-3]

Shrinking (6 time(s))
[0,0]
false
6> proper:quickcheck(demo:prop_same_length()).
.............!
Failed: After 13 test(s).
[2,-8,-3,1,1]

Shrinking (1 time(s))
[1,1]
false
```

```
sort([]) -> [];
sort([P|Xs]) ->
  sort([X || X <- Xs, X < P])
  ++ [P] ++
  sort([X || X <- Xs, P < X]).
```

# Integration with simple types

```
%% Using a user-defined simple type as a generator
-type bf() :: binary() | 'apple' | 'banana' | 'orange'.

prop_same_length() ->
  ?FORALL(L, list(bf()),
          length(L) =:= length(sort(L))).
```

```
7> c(demo).
{ok,demo}
8> proper:quickcheck(demo:prop_same_length()).
.................!
Failed: After 17 test(s).
[banana,apple,<<134>>,banana,<<42,25,177>>]

Shrinking (2 time(s))
[banana,banana]
false
```

# Integration with complex types

```
%% Using a user-defined recursive type as a generator
-type bf() :: binary() | 'apple' | 'banana' | 'orange'.
-type tree(T) :: 'leaf' | {'node',T,tree(T),tree(T)}.

prop_same_length() ->
  ?FORALL(L, list(tree(bf())),
          length(L) =:= length(sort(L))).
```

```
9> c(demo).
{ok,demo}
10> proper:quickcheck(demo:prop_same_length()).
...............!
Failed: After 15 test(s).
[{node,banana,{node,<<42>>,leaf,leaf},leaf},...]

Shrinking (2 time(s))
[{node,banana,{node,banana,leaf,leaf},leaf},
 {node,banana,{node,banana,leaf,leaf},leaf}]
false
```

# PBT of sensor networks

- Sensor network:

  Random distribution of UDB server and client nodes

  Client node periodically sends messages to server node

- Property to test:

  Has X-MAC for any network a

  duty-cycle > 25%?

(duty-cycle ::= % time the radio is on)

# User-defined generators

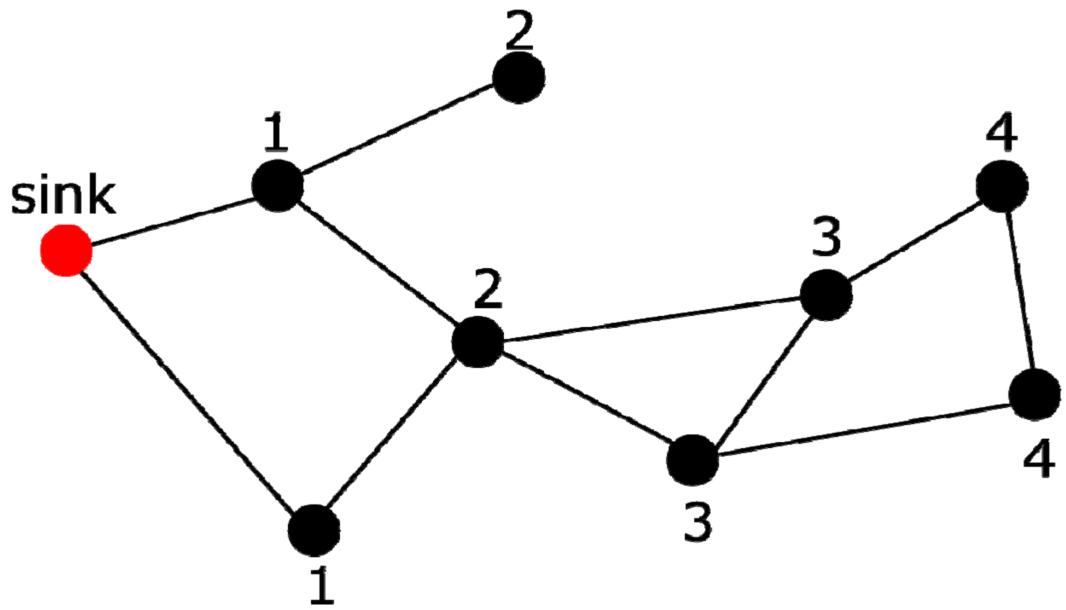
A generator for random graphs of **N** nodes:

```
graph(N) ->
  Vs = lists:seq(1, N),
  ?LET(Es, list(edge(Vs)), {Vs,lists:usort(Es)}).

edge(Vs) ->
  ?SUCHTHAT({V1,V2}, {oneof(Vs),oneof(Vs)}, V1 < V2).
```

**Great**: We can generate random sensor networks!

# Node distances




On this graph, the maximum distance to sink is 4.

Is there a network with **N** nodes where the max distance to a sink node is greater than **N/2**?

# Testing the max_distance property

```
prop_max_distance(N) ->
  ?FORALL(G, graph(N),
          begin
            D = lists:max(distance_to_sink(G)),
            D < (N div 2)
          end).
```

```
2> proper:quickcheck(demo:prop_max_distance(42)).
.......... 100 dots ..........
OK: Passed 100 tests
true
3> proper:quickcheck(demo:prop_max_distance(42), 100000).
.......... 100000 dots ..........
OK: Passed 100000 tests
true
```

# Possible solutions

- Write more involved (custom) generators.

- Guide the input generation

  using a search strategy, and

  introducing a feedback-loop in the testing.

# Targeted Property-Based Testing

- Combines search techniques with PBT.
- Automatically guides input generation towards inputs with high probability of failing.

- Gather information during test execution in the form of **utility values** (**UVs**).
- UVs capture how close input came to falsifying a property.

# Targeted max_distance property

```
prop_max_distance(N) ->
  ?FORALL_SA(G, ?TARGET(#{gen => graph(N)}),
          begin
            D = lists:max(distance_to_sink(G)),
            ?MAXIMIZE(D),
            D < (N div 2)
          end).
```

Utility value

Now the **`prop_max_distance(42)`** property

fails consistently with only a few thousand tests!

# Testing the X-MAC protocol

Random PBT

Average amount of tests: **1188**

Average time per tests: 23.5s

**Mean Time to Failure: 7h46m**

Targeted PBT

Average amount of tests: **200**

Average time per tests: 40.6s

**Mean Time to Failure : 2h12m**

# Testing security properties

$$\frac{i(pc) = \mathit{Noop}}{\boxed{pc \mid s \mid m} \Rightarrow \boxed{pc{+}1 \mid s \mid m}} \qquad (\textsc{Noop})$$

$$\frac{i(pc) = \mathit{Push}\ v}{\boxed{pc \mid s \mid m} \Rightarrow \boxed{pc{+}1 \mid v : s \mid m}} \qquad (\textsc{Push})$$

$$\frac{i(pc) = \mathit{Pop}}{\boxed{pc \mid v : s \mid m} \Rightarrow \boxed{pc{+}1 \mid s \mid m}} \qquad (\textsc{Pop})$$

Definitions for an abstract machine.

Test: Do these definitions fulfill a certain security criteria?

(**Noninterference**)

Cătălin Hrițcu et al. "Testing noninterference, quickly." *Journal of Functional Programming,* 26 (2016).

# Testing security properties

Random PBT

**Naive**: generate random programs

**ByExec**: generate program step-by-step one instruction a time;
new instruction should not crash program

| | Random PBT | |
|---|---|---|
| | Naive | ByExec |
| ADD | 2234,08ms | 312,97ms |
| LOAD | 324028,34ms | 987,91ms |
| STORE A | *timeout* | 4668,04ms |

# Testing security properties

Targeted PBT

**List**: programs are a list of instructions; using the built-in list generator for Simulated Annealing

**ByExec**: neighboring program: a program with one more instruction

| | **Random PBT** | | **Targeted PBT** | |
|---|---|---|---|---|
| | Naive | ByExec | List | ByExec |
| ADD | 2234,08 | 312,97 | 319,86 | 68,49 |
| LOAD | 324028,34 | 987,91 | 287,23 | 135,52 |
| STORE A | – | 4668,04 | 1388,09 | 263,94 |

# Testing security properties

hand written; ca. 30 lines of additional code

| | PBT | | Targeted PBT | |
|---|---|---|---|---|
| | Naive | ByExec | List | ByExec |
| ADD | 2234,08 | 312,97 | 319,86 | 68,49 |
| LOAD | 324028,34 | 987,91 | 287,23 | 135,52 |
| STORE A | – | 4668,04 | 1388,09 | 263,94 |

1 line of code!

# Concuerror – concuerror.com

# Stateless Model Checking (SMC)

aka **Systematic Concurrency Testing**

A technique to **detect** concurrency errors or **verify** their absence by exploring all possible ways that concurrent execution can influence a program's outcome.

fully automatic

low memory requirements

applicable to programs with finite executions

# How SMC works

Assume that you only have one ‘scheduler’.

- Run an arbitrary execution of the program...

Then:

- Backtrack to a point where some other thread could have been chosen to run…
- From there, continue with another execution…

Repeat until all choices have been explored.

# Systematic exploration example

Initially: x = y = 0

**Thread 1**

```
x := 1;
y := 1;
```

**Thread 2**

```
x := 2;
y := 2;
```

**Correctness Property (at the end)**

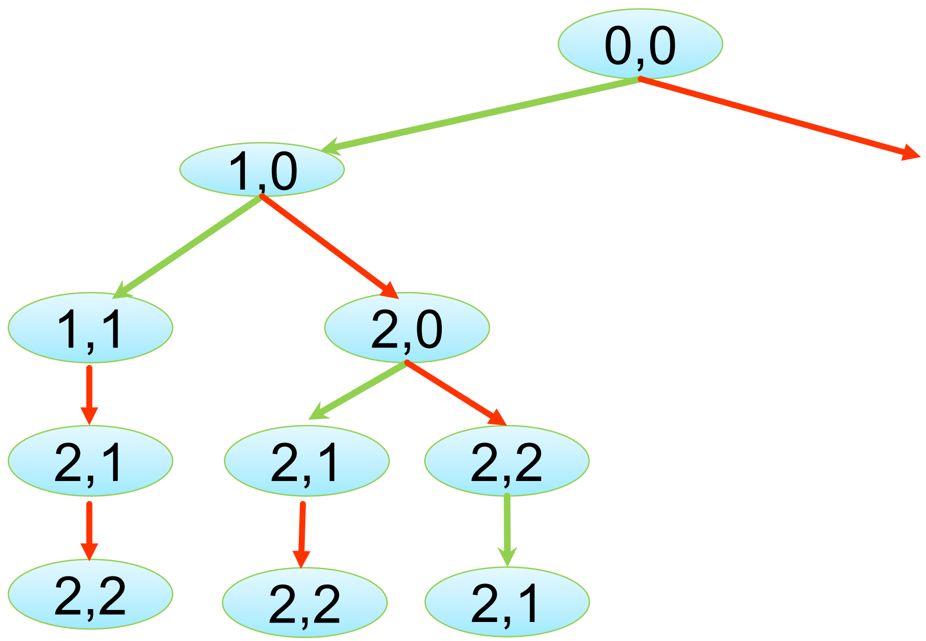
```
assert(x == y);
```

```
x := 1;
```

```
y := 1;
```

```
x := 2;
```

```
y := 2;
```




Exploration can stop early when a property is violated.

# Systematic exploration example

Initially: x = y = 0

**Thread 1**

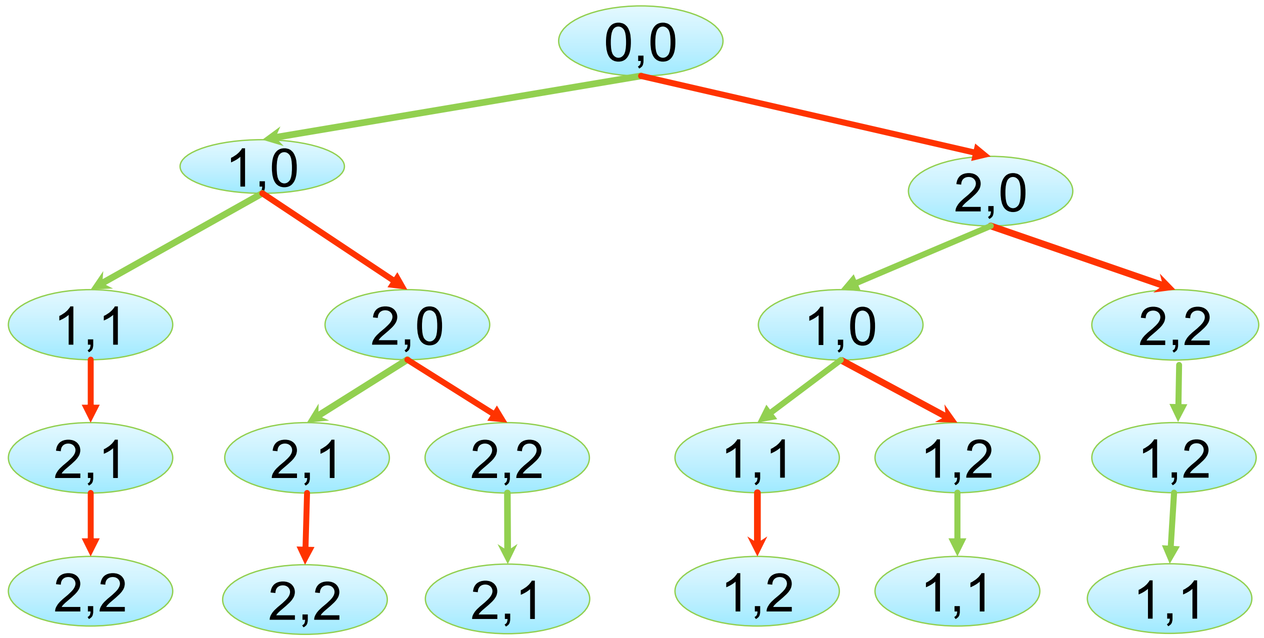
```
x := 1;
y := 1;
```

**Thread 2**

```
x := 2;
y := 2;
```

**Correctness Property (at the end)**

```
assert((x + y) < 7);
```




Exploration needs to visit the <u>complete</u> set of traces for properties that hold.

# Concuerror

A **stateless model checker** for **Erlang** that systematically explores **all** possible behaviours of a program annotated with some assertions, to

either detect concurrency errors

(in which case it reports the erroneous trace)

or verify their absence

(i.e., that the properties in the assertions hold)

# Systematic ≠ Stupid

Literally explore “all traces”?? Too many!

Not all pairs of events are conflicting.

Each explored trace should be **different**.

# Partial Order Reduction (POR)

Combinatorial explosion in the number of interleavings.

Initially: x = y = … = z = 0

| Thread 1: | Thread 2: | Thread N: |
| --- | --- | --- |
| x := 1 | y := 1 | z := 1 |

- Interleavings under naïve exploration: **N!**
- Interleavings needed to cover all behaviors: **1**

## Partial Order Reduction (POR)

✓ Explore just a subset of all interleavings

✓ Still cover all behaviors

# Optimal DPOR [POPL'14,JACM'17]

The exploration algorithm

… monitors **conflicts** between events;

… explores additional interleavings **as needed**;

… completely avoids **equivalent** interleavings.

**Dynamic**: at runtime, using concrete data.

**Optimal**:

explores only one interleaving per equivalence class;

does not even initiate redundant ones.

# Optimal DPOR exploration

Initially: x = y = 0

**Thread 1**

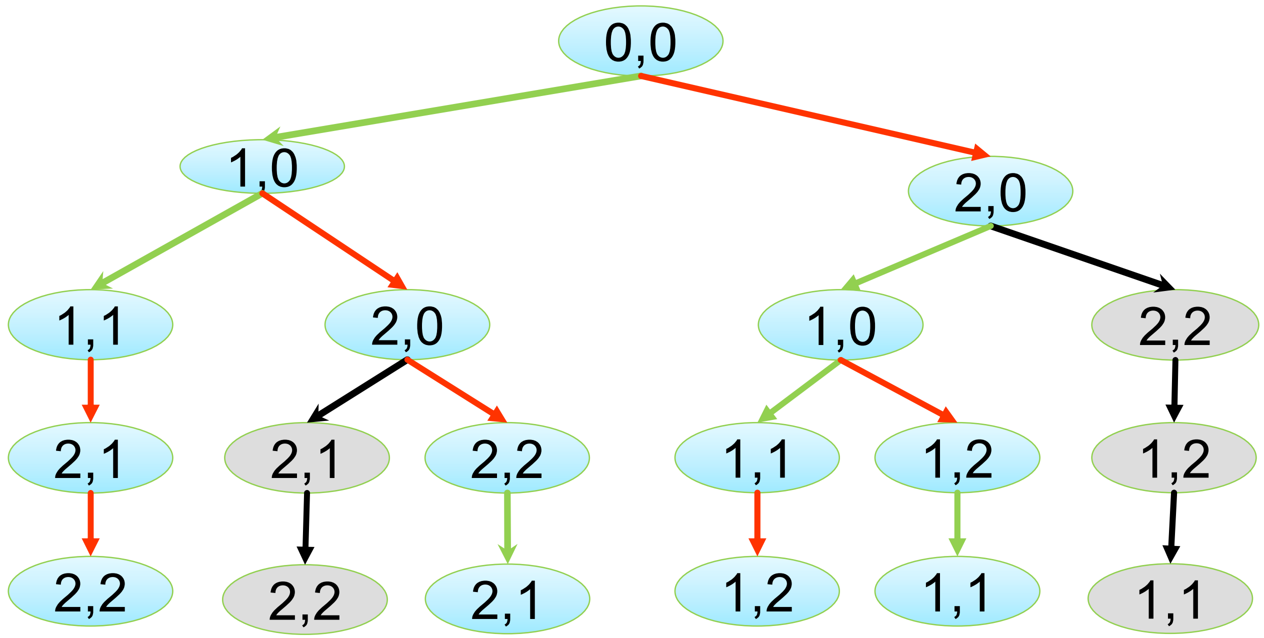
```
x := 1;
y := 1;
```

**Thread 2**

```
x := 2;
y := 2;
```

**Correctness Property (at the end)**

```
assert((x + y) < 7);
```




Optimal DPOR will not be explore the grey nodes.

# Bounding

Explore only a few traces based on some bounding criterion.

- E.g., number of times threads can be preempted, delayed, etc.

Very effective for testing!

Not suitable for verification.

# Preemption bounded exploration

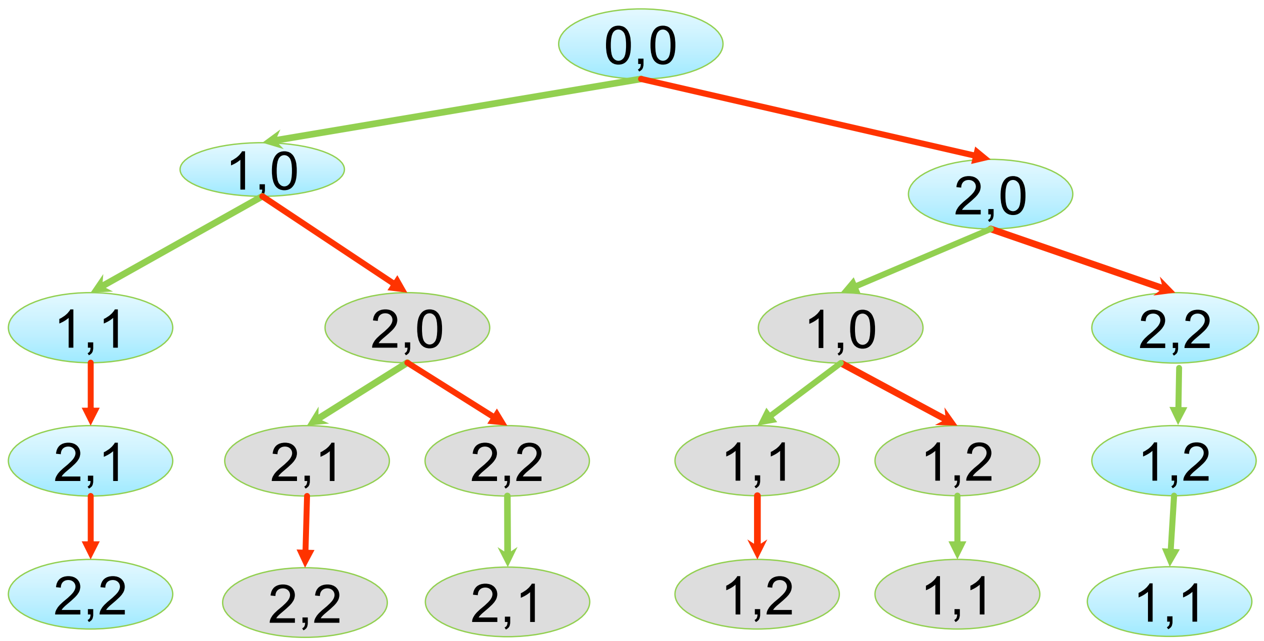
Initially: x = y = 0

Thread 1

```
x := 1;
y := 1;
```

Thread 2

```
x := 2;
y := 2;
```




With a **preemption bound** of **0**,
the grey nodes will not be explored.

# Preemption bounded exploration

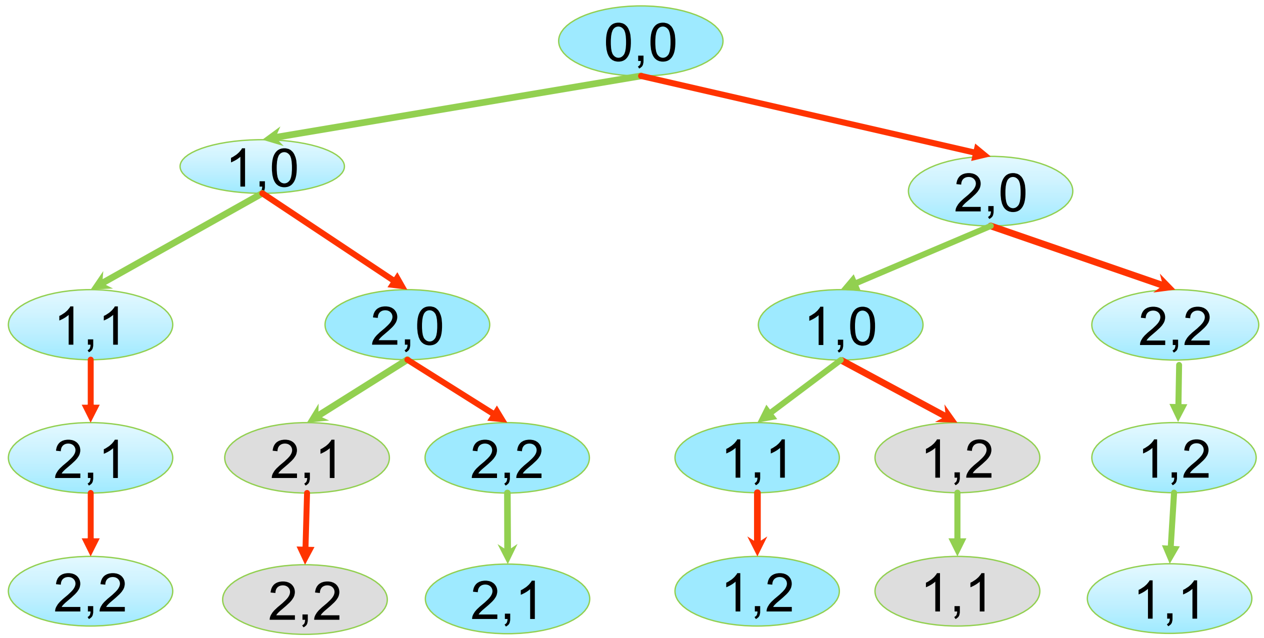
Initially: x = y = 0

**Thread 1**

```
x := 1;
y := 1;
```

**Thread 2**

```
x := 2;
y := 2;
```




With a **preemption bound** of **1**, the grey nodes will not be explored.

# Chain replication [OSDI'04]

A variant of master/slave replication.

Strict chain order:

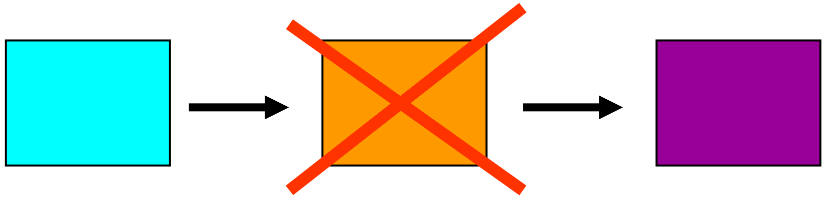

Sequential read @ tail.

Linearizable read @ all.

Dirty read @ head or middle.

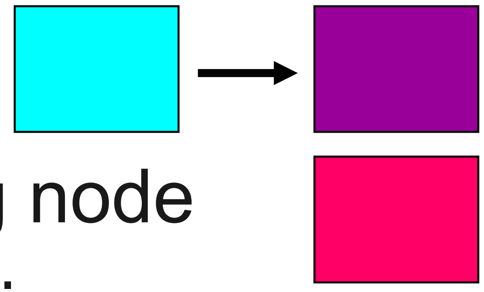
# Chain repair

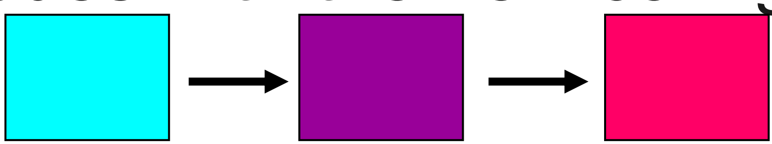
Suppose chain of three servers:



Naive offline repair method:

1. Stop all surviving servers in the chain
2. Copy tail's update history to the repairing node
3. Restart all nodes with the new configuration





A better repair method for CR systems places the repairing node directly on the chain and reads go to  (the old tail).

# CORFU [SIGOPS'12,NSDI'17]

Uses Chain Replication with three changes:

1. Responsibility for replication is moved to the client.

2. CORFU's servers implement <u>write-once semantics.</u>

3. Identifies each chain configuration with an <u>epoch #.</u>
   - All clients and servers are aware of the epoch #.
   - The server rejects clients with a different epoch #.
   - A server temporarily stops service if it receives a newer epoch # from a client.

# Engineers at VMWare (1)

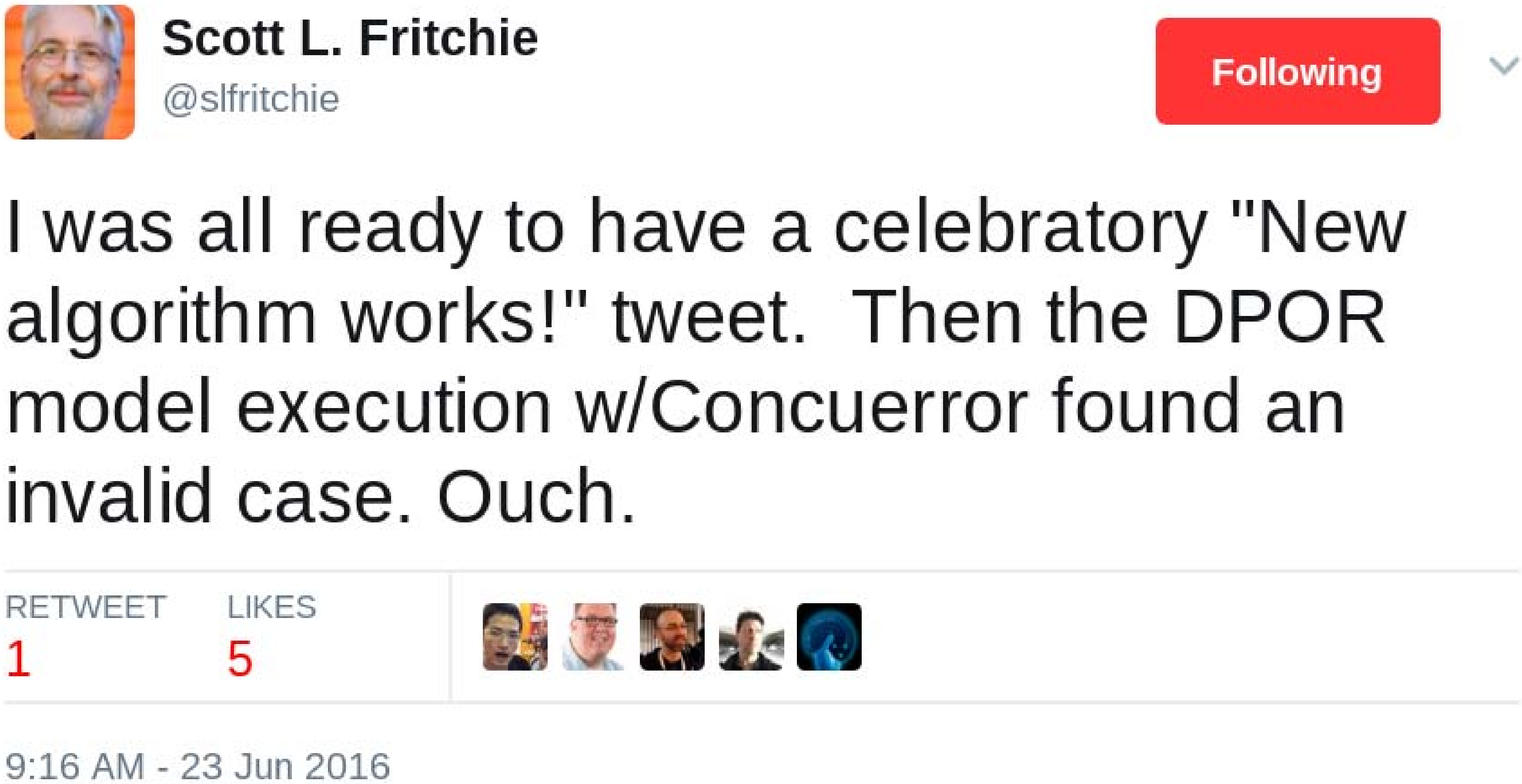
Investigated methods for chain repair in CORFU

Method #1: Add to the tail

# Engineers at VMWare (2)

Investigated methods for chain repair in CORFU

Method #2: ~~Add to the head~~



# Modeling CORFU in Erlang

**Initial model:**

• Some (**one** or **two**) servers undergo a chain repair to add **one** more server to their chain.

• Concurrently, **two** other clients try to write **two** different values to the same key.

• While a third client tries to read the key **twice**.

# Modeling CORFU in Erlang (cont)

- Servers and clients are modeled as Erlang processes.
- All requests are modeled as messages.

Processes used by the model:

- Central coordinator
- CORFU log servers (2 or 3)
- Layout server process
- CORFU reading client
- CORFU writing clients (2)
- Layout change and data repair process

# Correctness properties

**Immutability:**

Once a value has been written in a key, no other value can be written to it.

**Linearizability:**

If a read sees a value for a key, subsequent reads for that key must also see the same value.

# Three repair methods

1. Add repair node at the tail of the chain.

2. Add repair node at the head of the chain.

3. Add repair node in the middle.
   - Configuration with two healthy servers.
   - Configuration with one healthy server which is "logically split" into two.

# Results in (old) Concuerror

| | Bounded Exploration | | | Unbounded Exploration | | |
|---|---|---|---|---|---|---|
| Method | Bug? | Traces | Time | Bug? | Traces | Time |
| 1 (Tail) | Yes | 638 | 57s | Yes | 3 542 431 | 144h |
| 2 (Head) | Yes | 65 | 7s | Yes | 389 | 26s |
| 3 (Middle) | No | 1257 | 68s | No | >30 000 000 | >750h |

# Model refinements

Conditional read

Avoid issuing read operations that are sure to not result in violations.

Convert layout server process to an ETS table (instead of a process).

# Effect of model refinements

Method #3 (add repair node in the middle)

Concuerror verifies the method

- in 48 hours
- after exploring 3 931 412 traces.

Method #1 (add repair node in the tail)

Even *without* bounding, the error is found in just 19 seconds (212 traces).