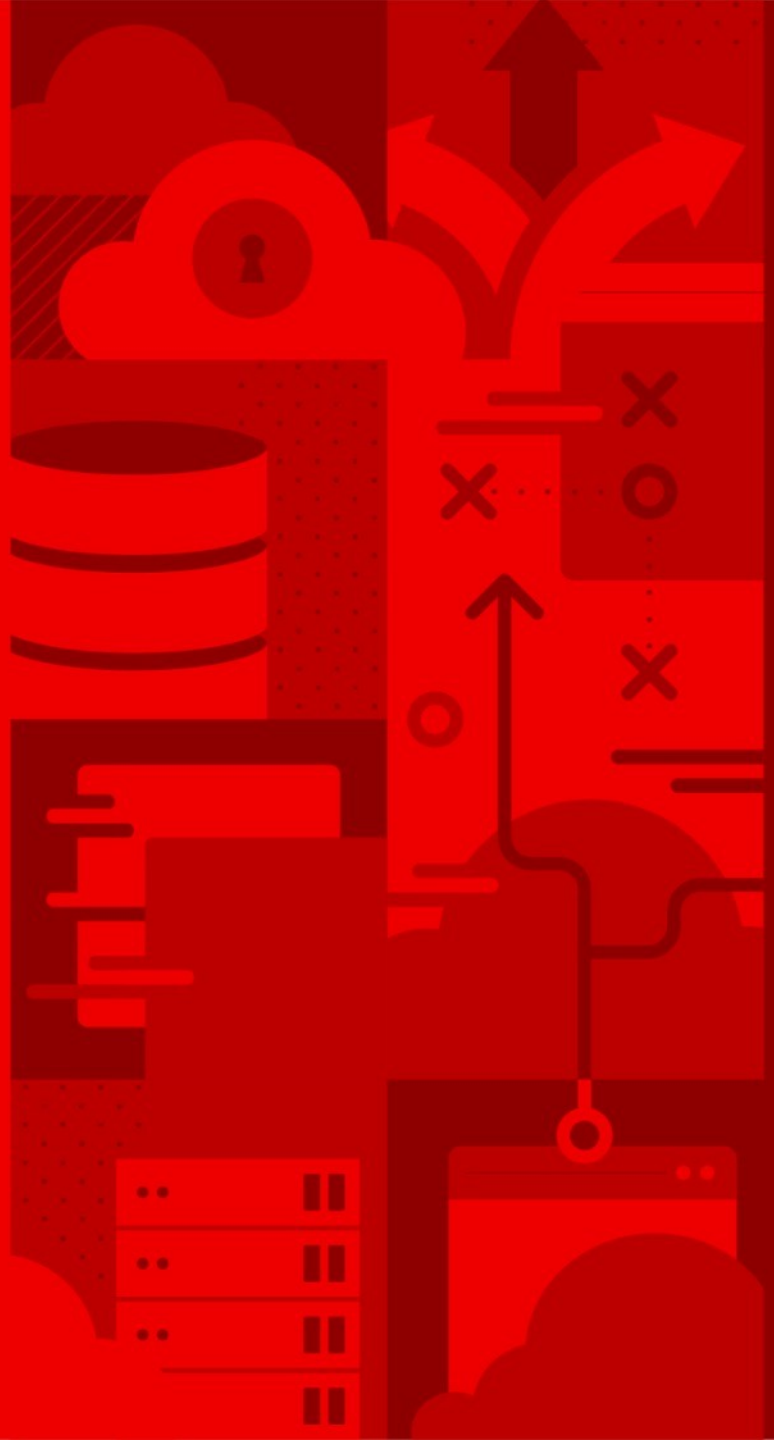
Formal modeling (and verification) made easy

And fast!

Daniel Bristot de Oliveira

Principal Software Engineer



Linux is complex.

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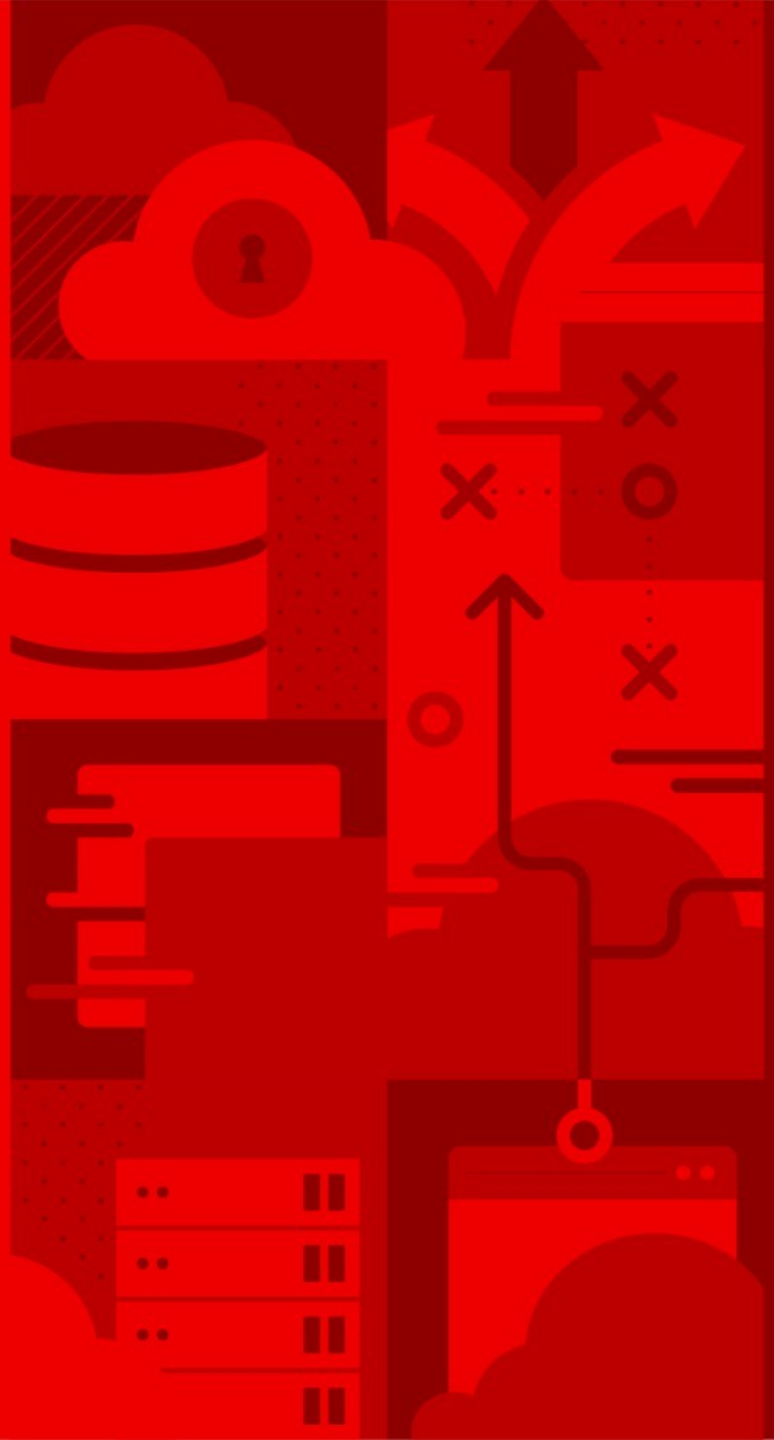

Linux is critical.

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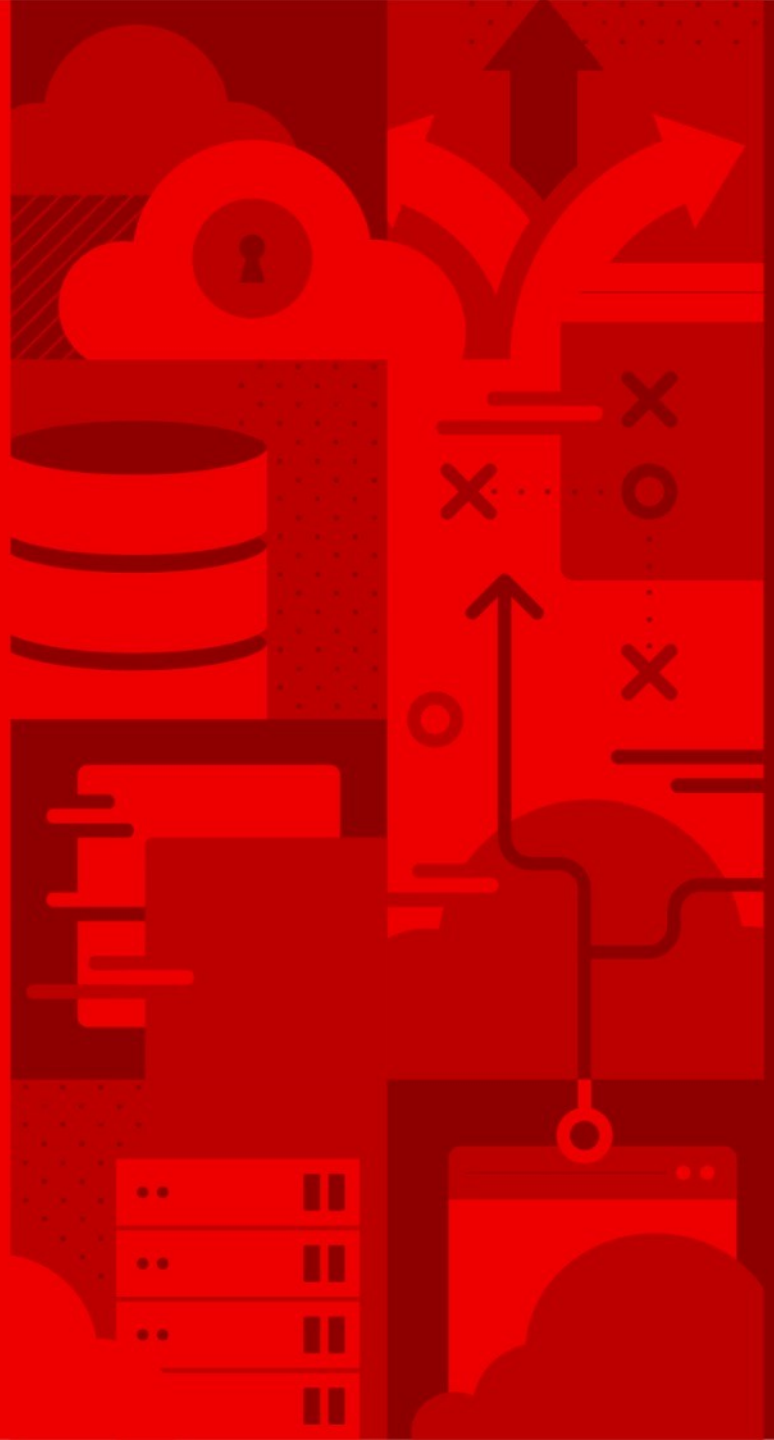
We need to be sure that Linux _*behaves*_ as _*expected*_ .



What do we _*expect*_?

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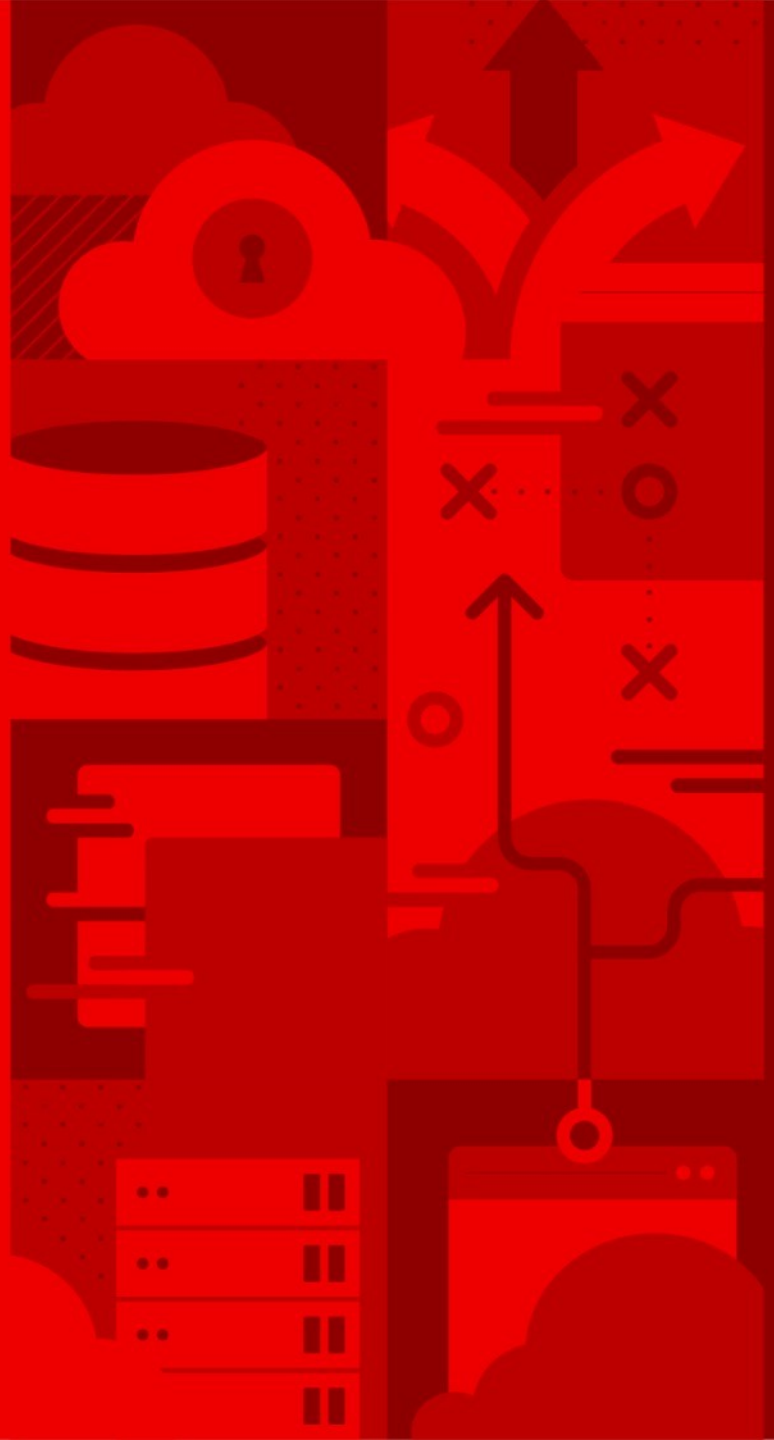
What do we _*expect*_?

- We have a lot of documentation explaining what is expected!
  - In many different languages!
- We have a lot of “ifs” that asserts what is expected!
- We have lots of tests that check if part of the system behaves as expected!



These things are good! But we need something more robust.

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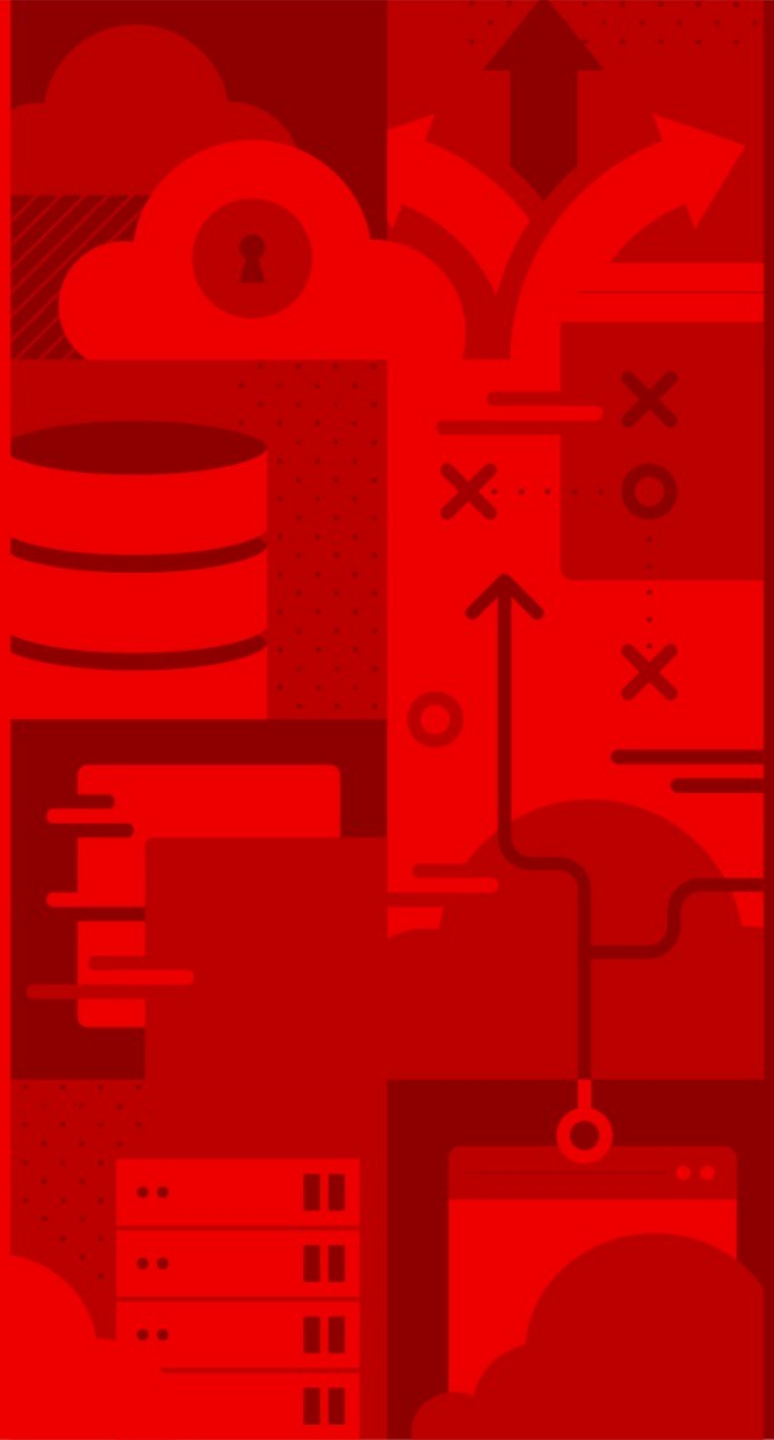
Like...

- How do we check that our reasoning is right?
- How do we check that our asserts are not contradictory?
- How do we check that we are covering all cases?
- How do we verify the runtime behavior of Linux?



How do we convince other communities about our properties?

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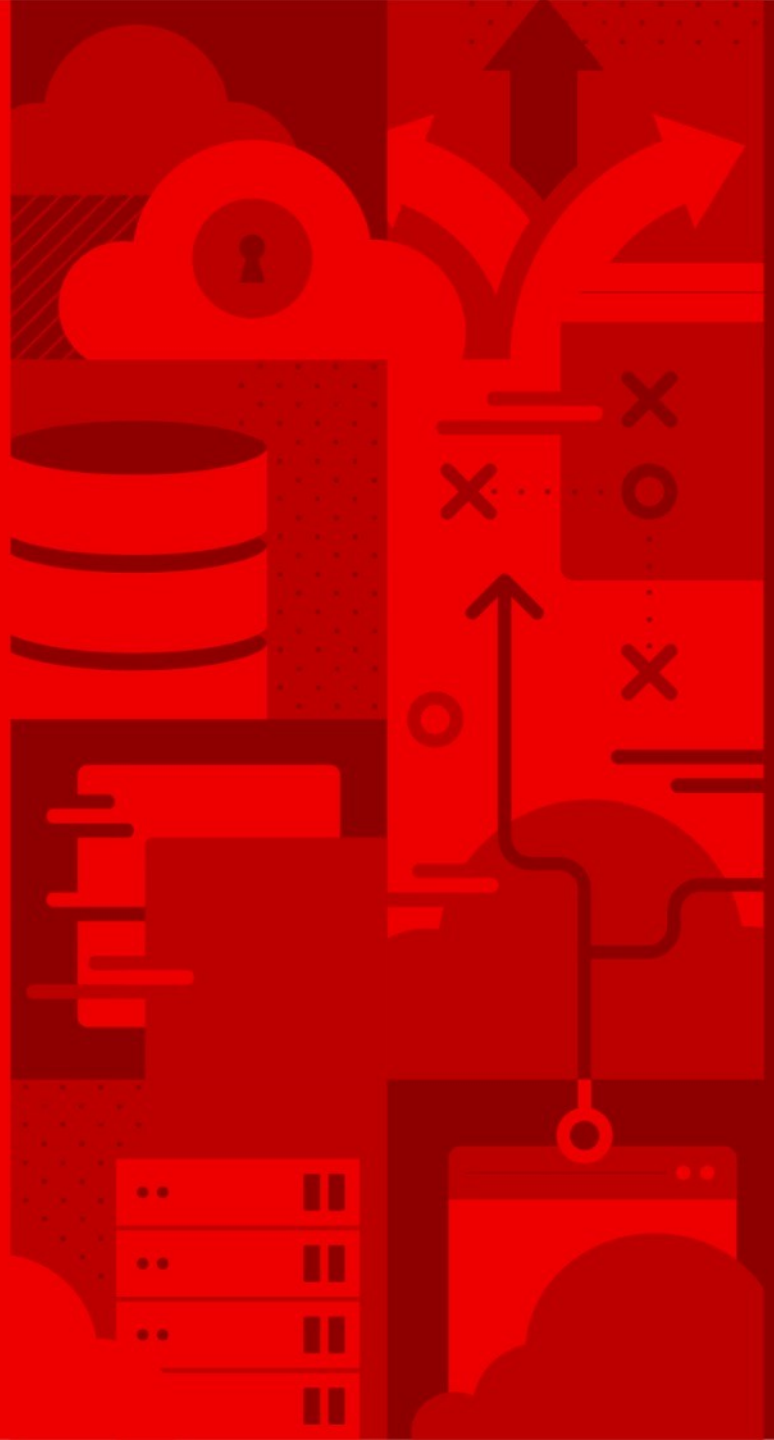
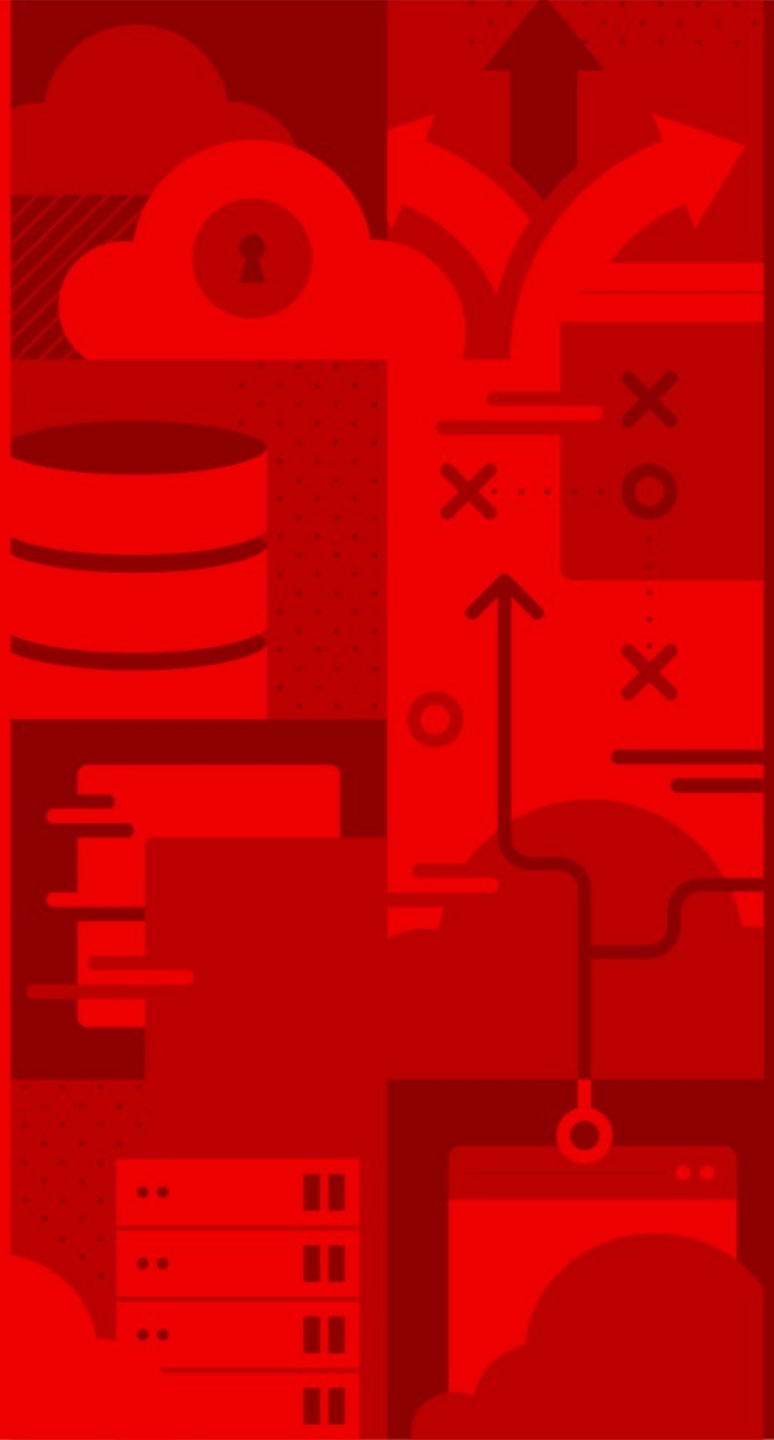


What computer scientists say about it?



Formal methods!

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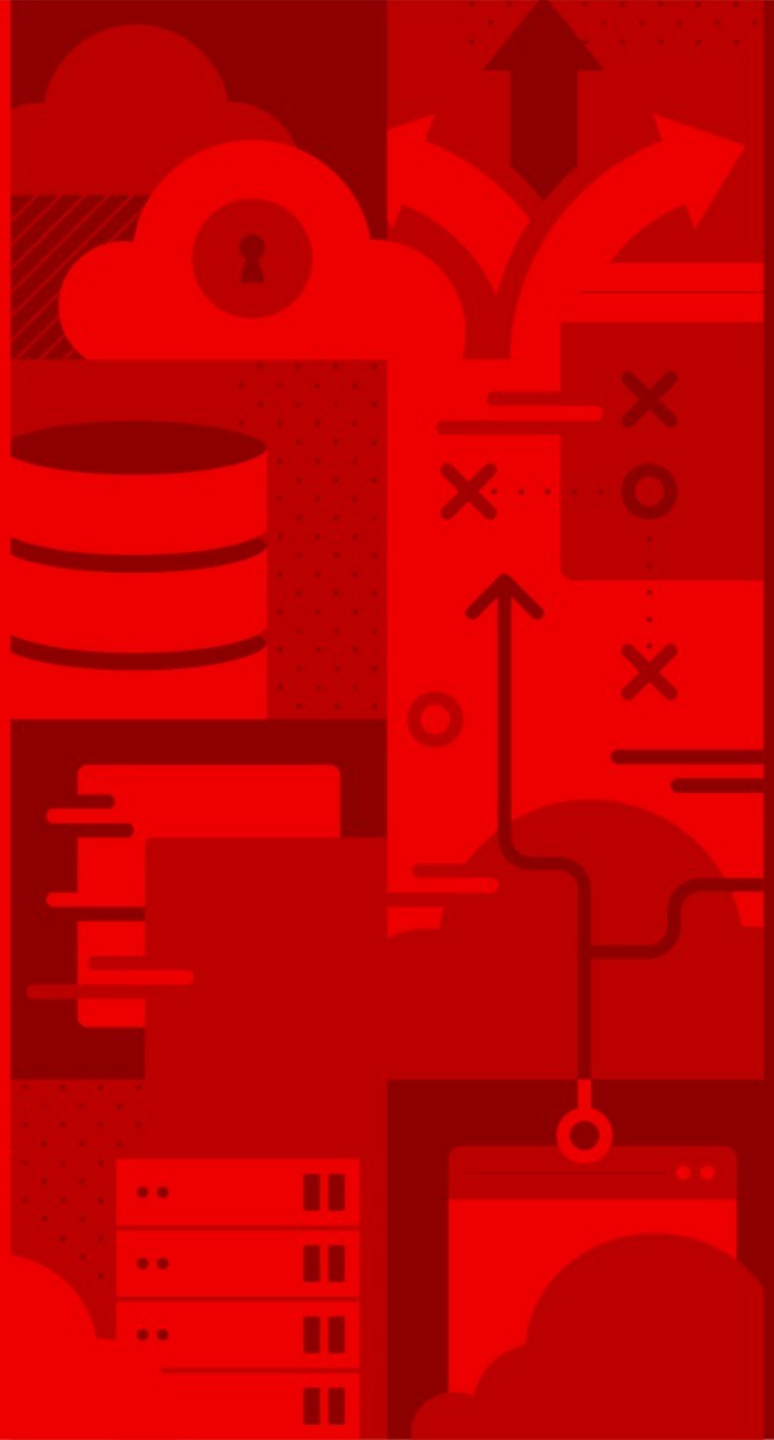
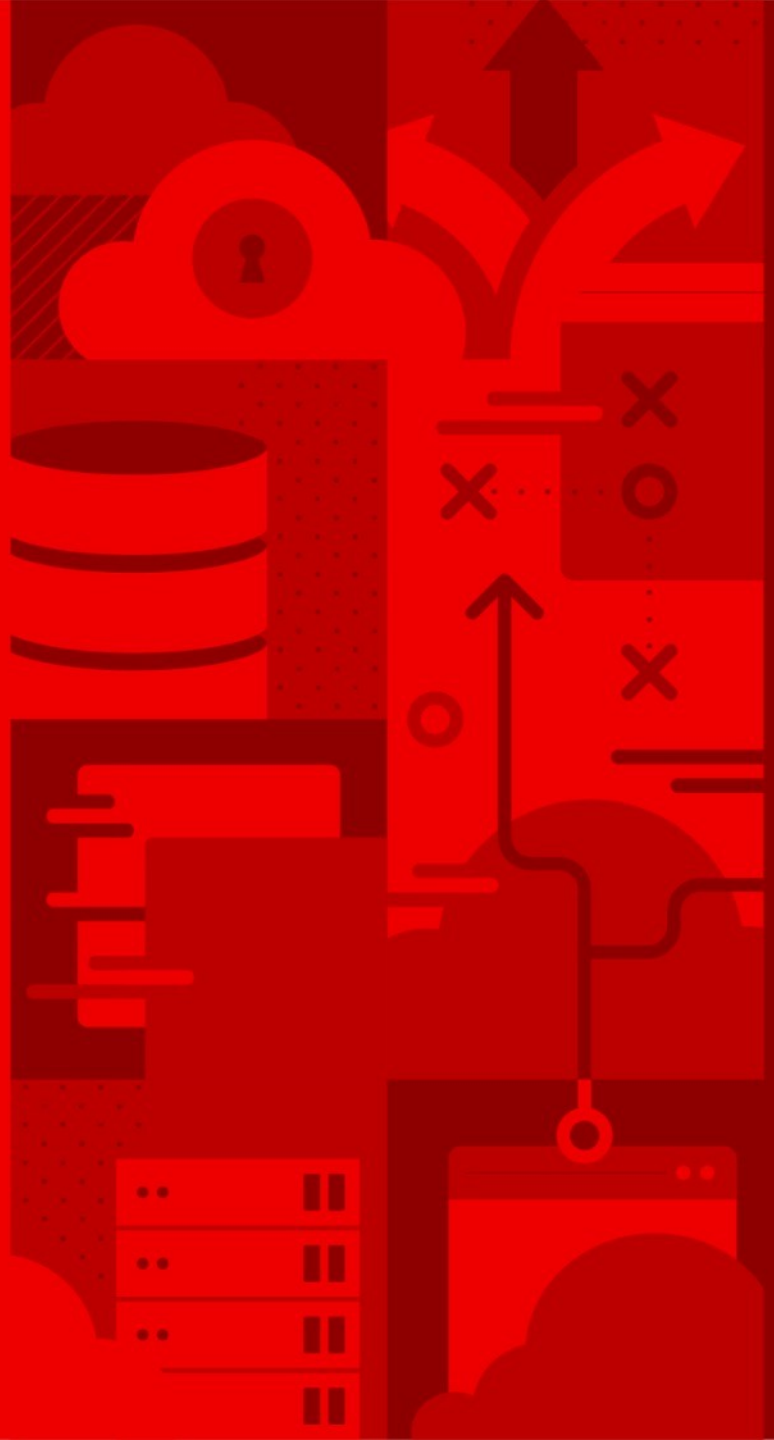


We already have some examples!



But we need a more “generic” and “intuitive way” for modeling.

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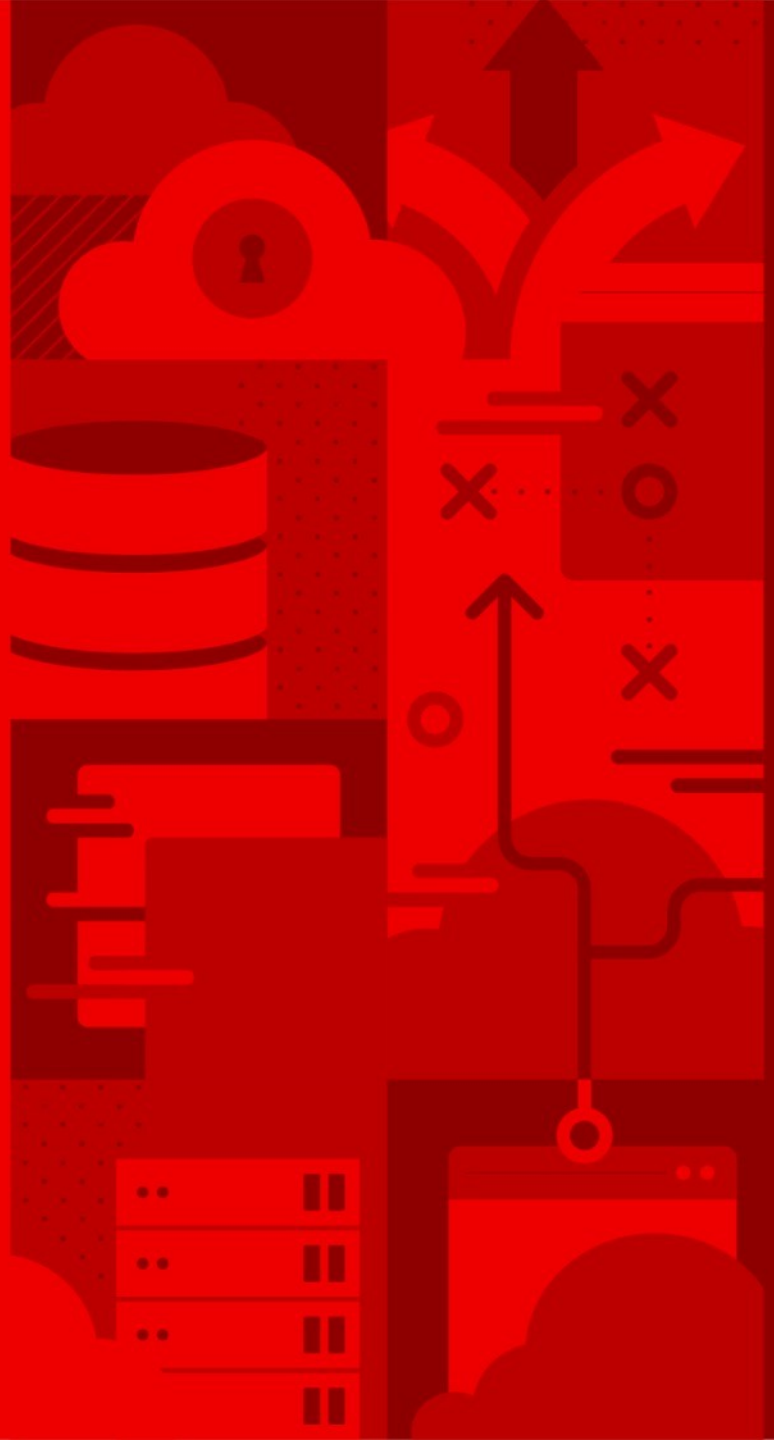
How can we turn modeling easier?

- Using a *formal language* that looks *natural* for us!
- How do we *naturally* “observe” the dynamics of Linux?



We trace events!

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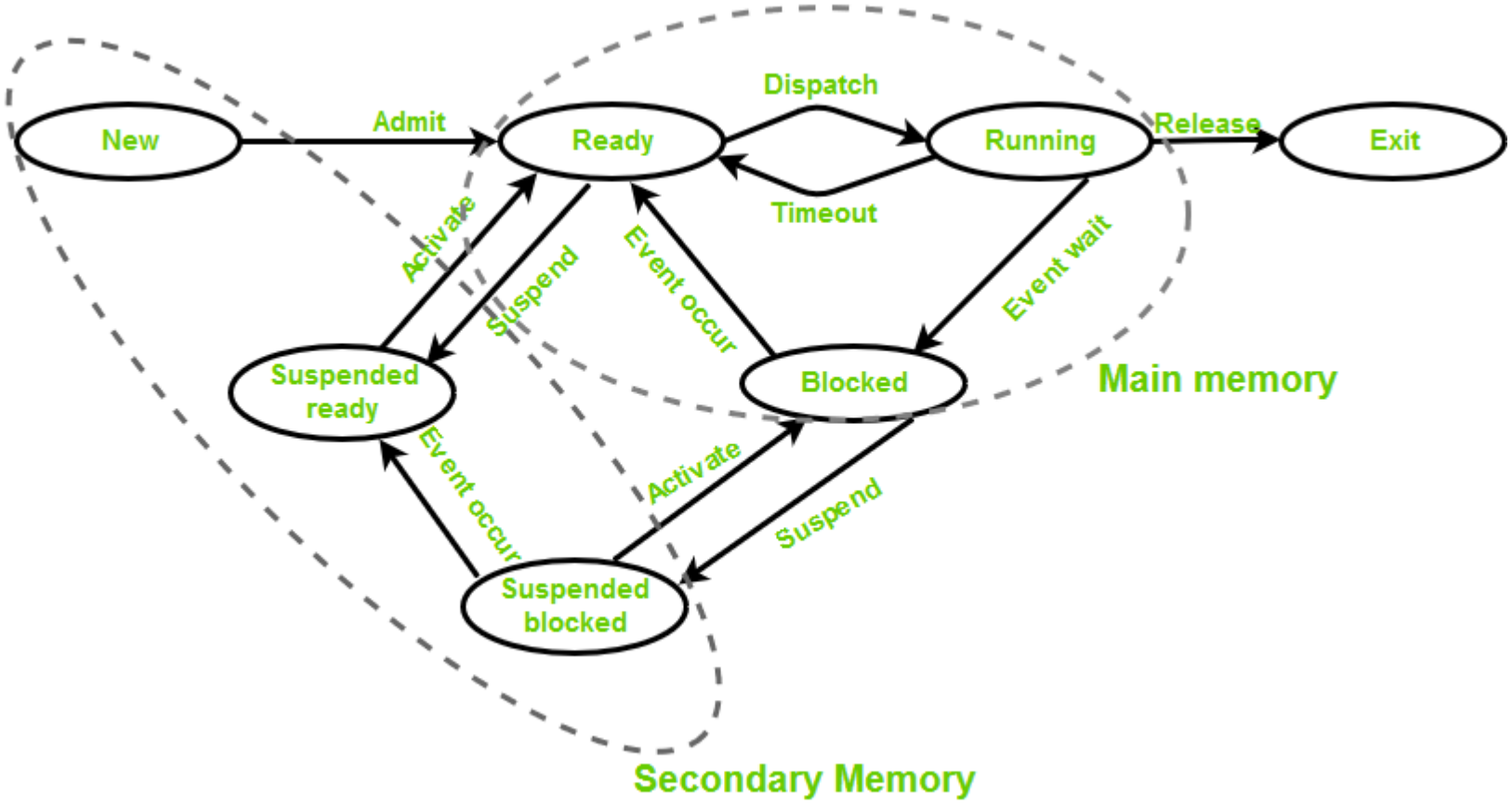
While tracing we...



^C^V from
https://www.geeksforgeeks.org/states-of-a-process-in-operating-systems/

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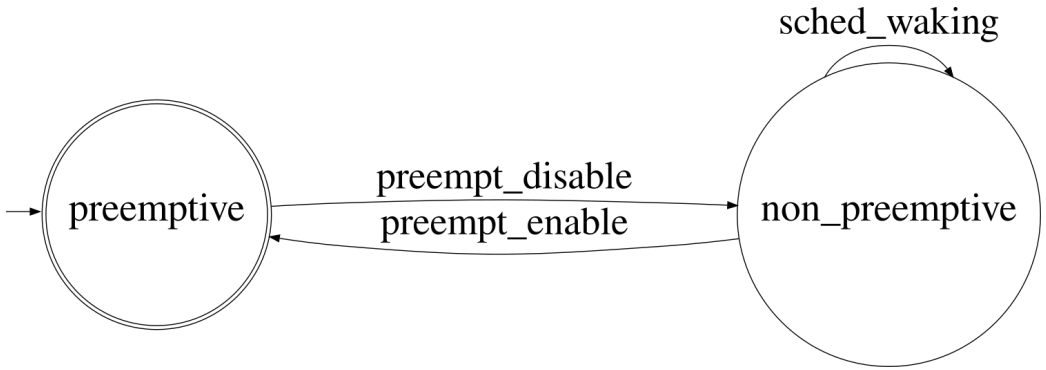
State-machines + FM = Automata!

- State machines are Event-driven systems
- Event-driven systems describe the system evolution as trace of events
- As we do for run-time analysis.

```
tail-5572  [001] ....1..  2888.401184: preempt_enable: caller=_raw_spin_unlock_irqrestore+0x2a/0x70 parent=         (null)
tail-5572  [001] ....1..  2888.401184: preempt_disable: caller=migrate_disable+0x8b/0x1e0 parent=migrate_disable+0x8b/0x1e0
tail-5572  [001] ....111  2888.401184: preempt_enable: caller=migrate_disable+0x12f/0x1e0 parent=migrate_disable+0x12f/0x1e0
tail-5572  [001] d..h212  2888.401189: local_timer_entry: vector=236
```



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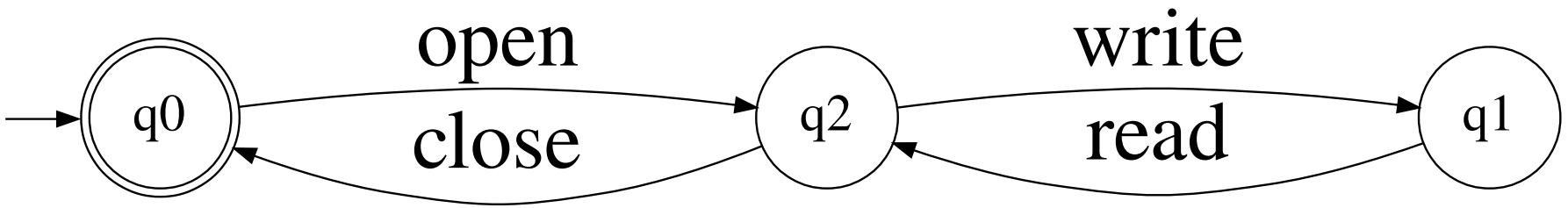
Using automata as formal language



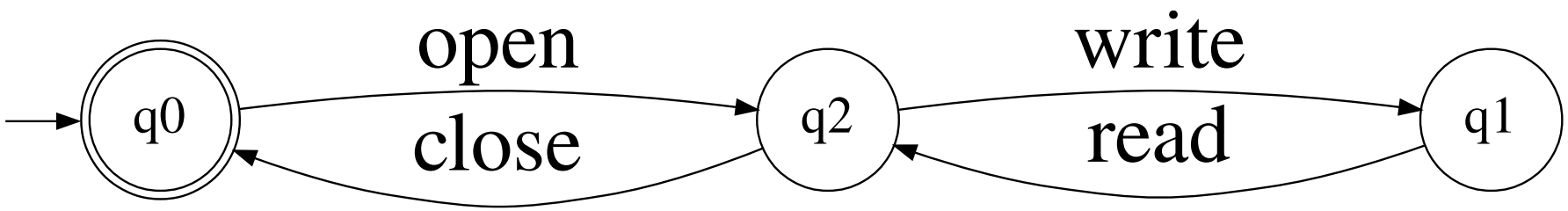
Is formally defined

- Automata is a method to model Discrete Event Systems (DES)
- Formally, an automaton G is defined as:
  - $G = \{X , E, f , x_0 , X_m \}$, where:
    - X = finite set of states;
    - E = finite set of events;
    - *F* is the transition function = $(X \times E) \rightarrow X$;
    - x_0 = Initial state;
    - X_m = set of final states.
- The language - or traces - generated/recognized by G is the L(G).

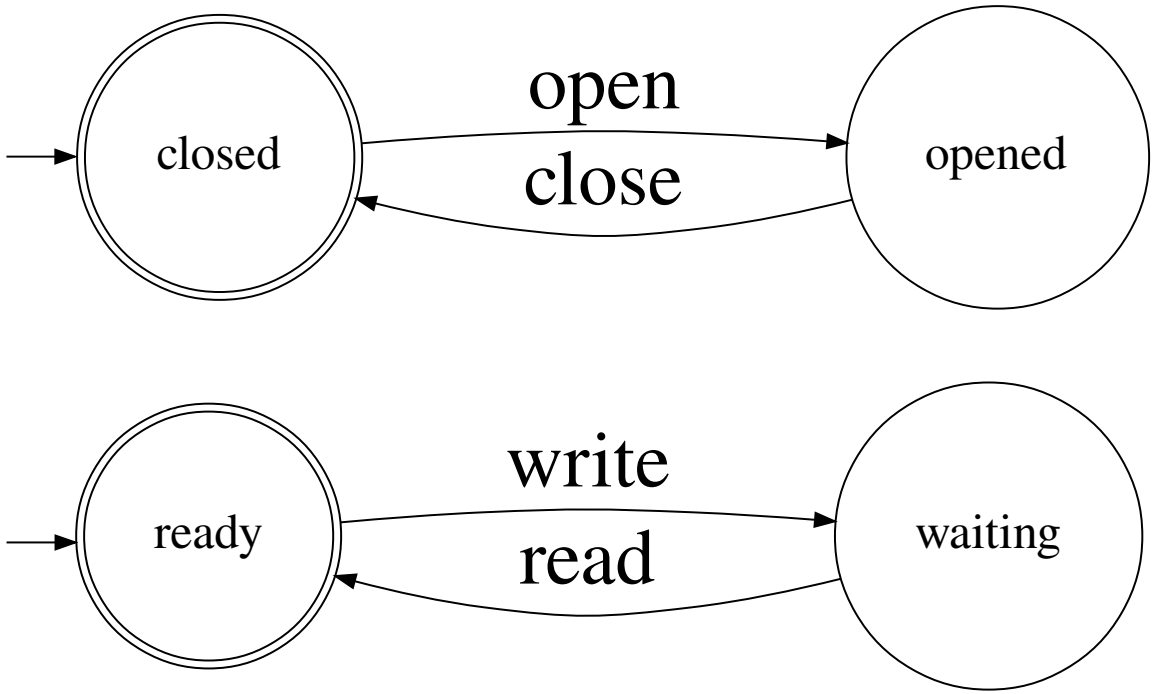
Automata allows

- The verification of the model
  - Deadlock free? Live-lock free?
- Operations
  - Modular development

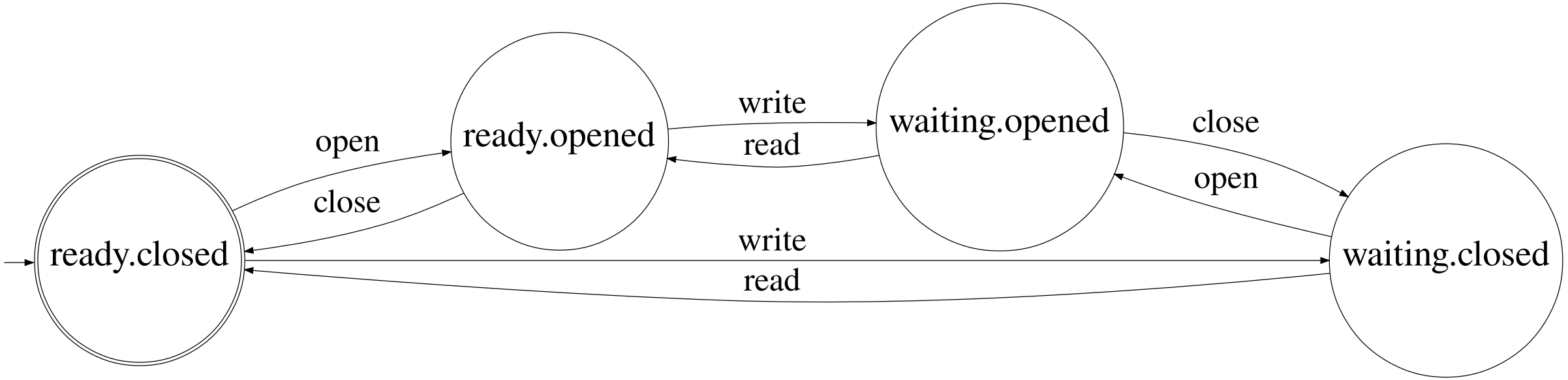
The previous example



Generators



Sync of generators



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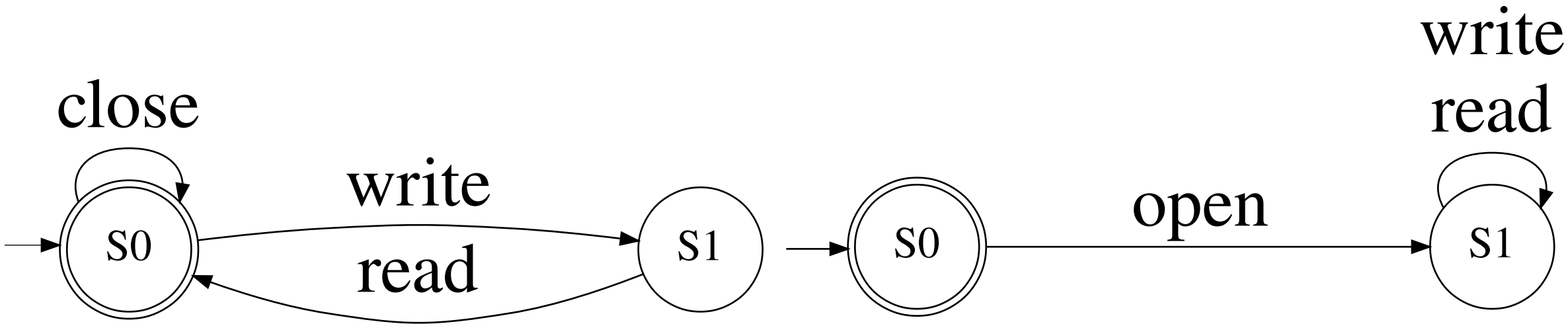
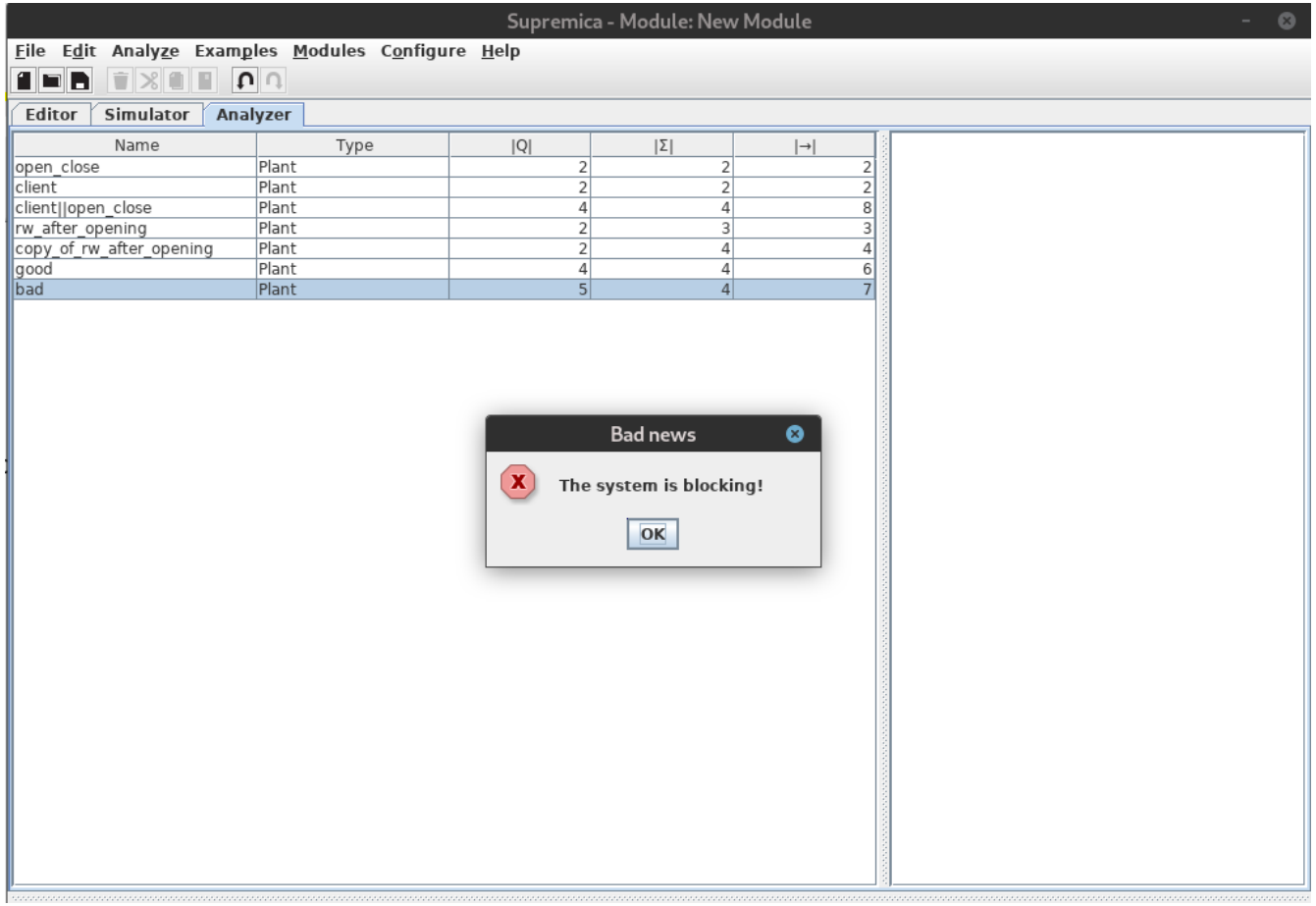
Specification



Verification



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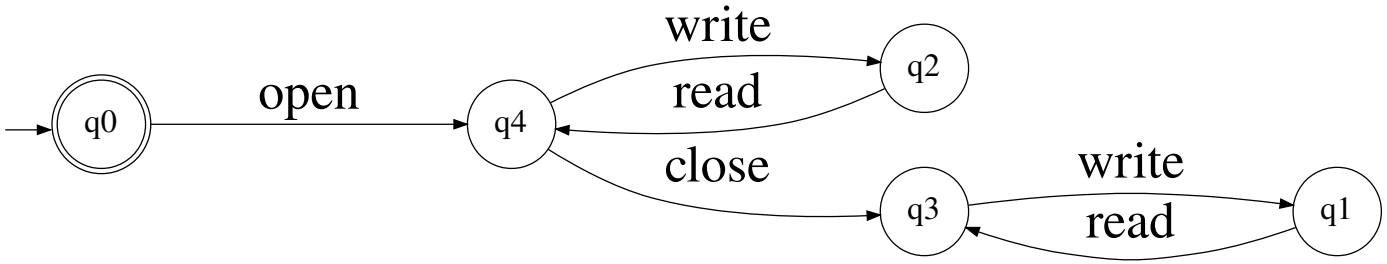
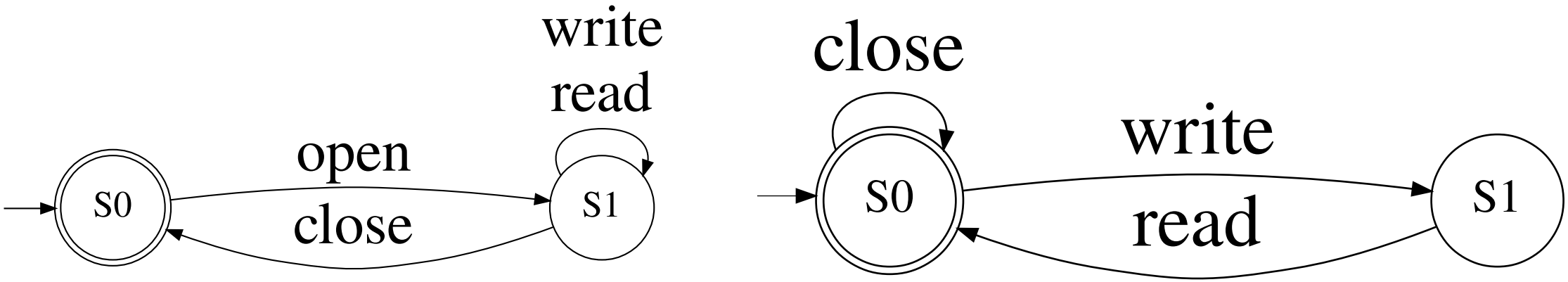
Synch of Generators and Specifications



Specifications



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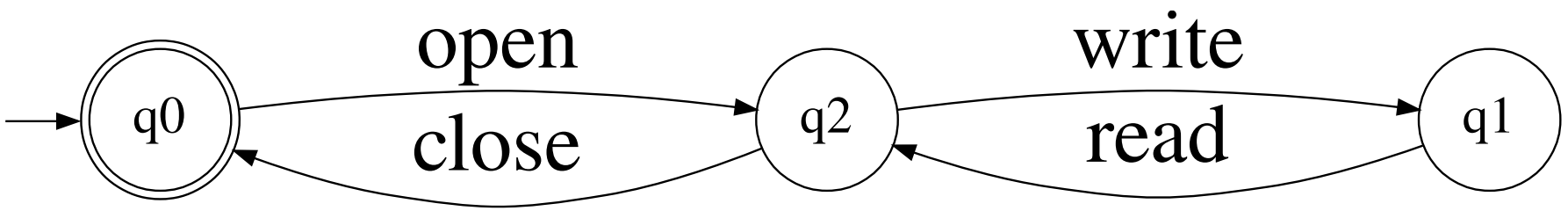
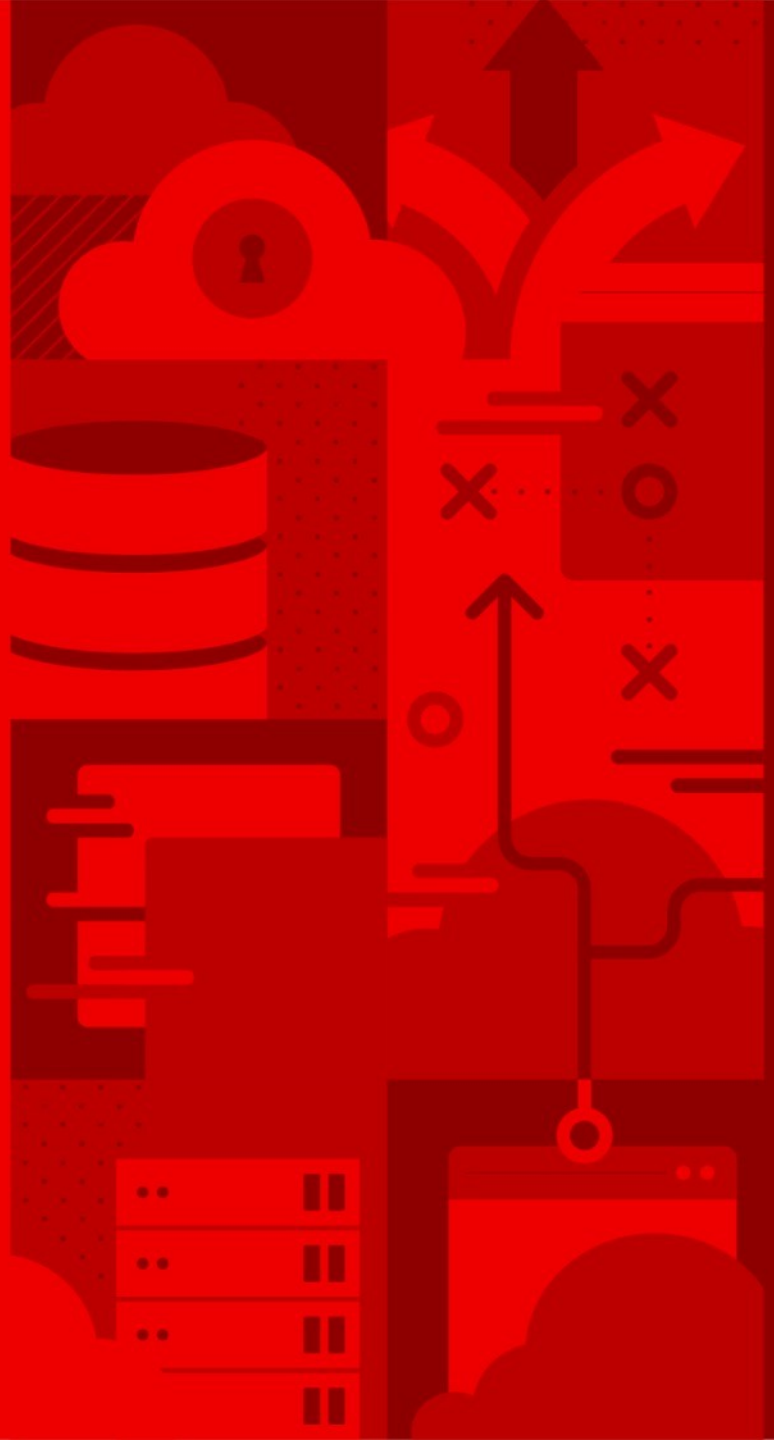
Sync of Generators and Specifications





Why not just draw it?

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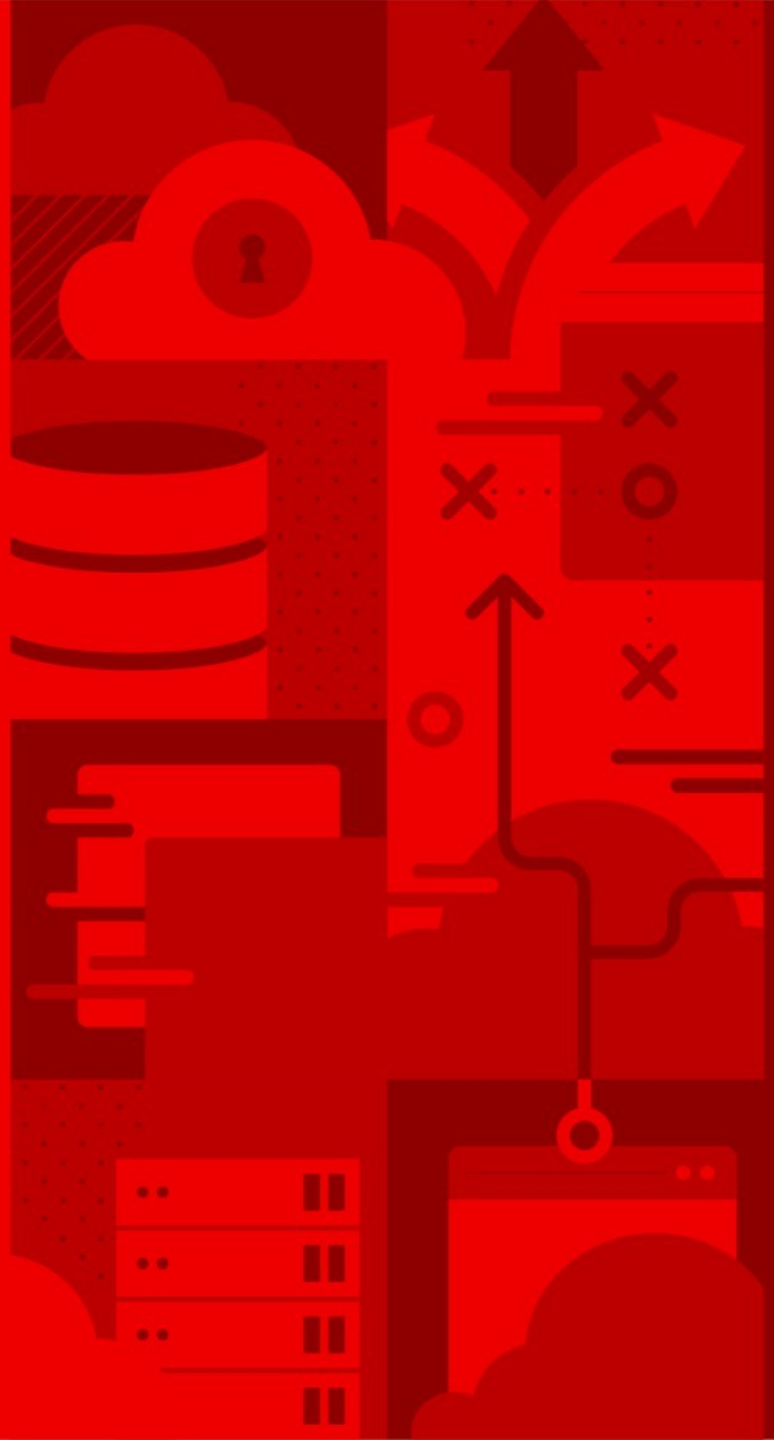

Linux is Complex!

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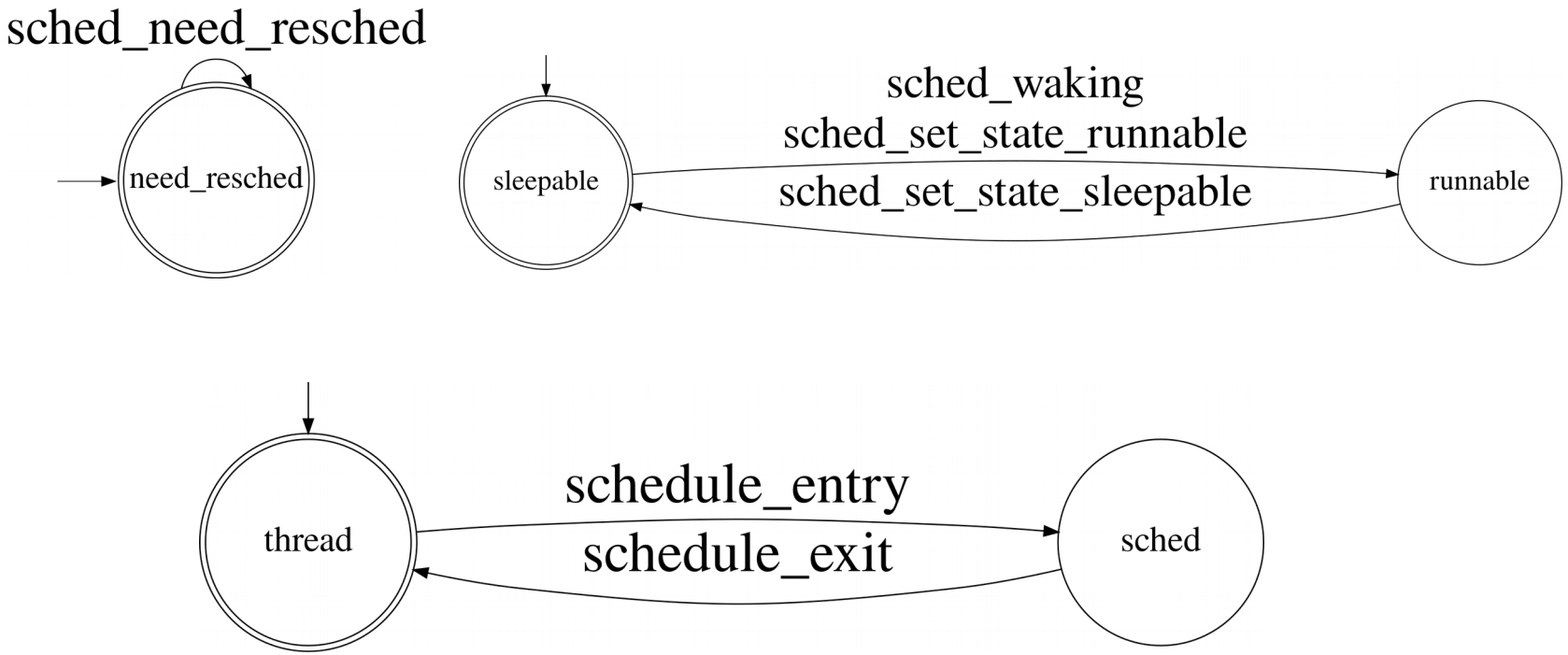
PREEMPT_RT model

- The PREEMPT RT task model has:
  - 9017 states!
  - 23103 transitions!
  - But:
    - 12 generators
    - 33 specifications
- During development found 3 bugs that would not be detected by other tools...

A more complex case



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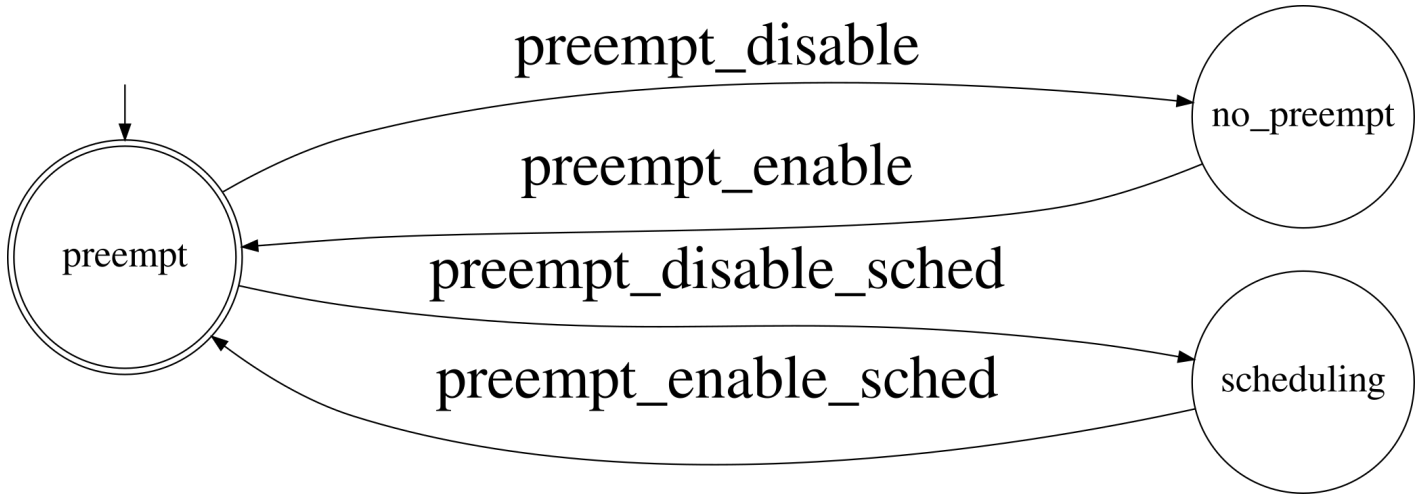
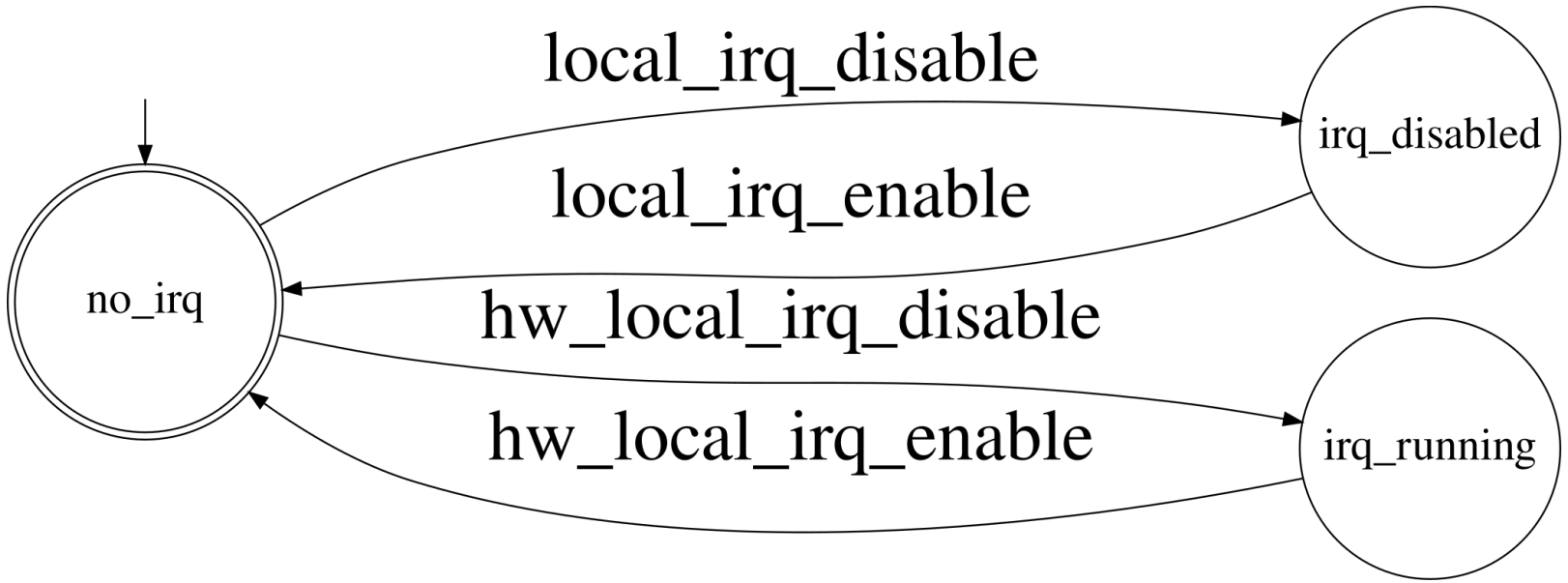
Independend “generators”



Independend “generators”



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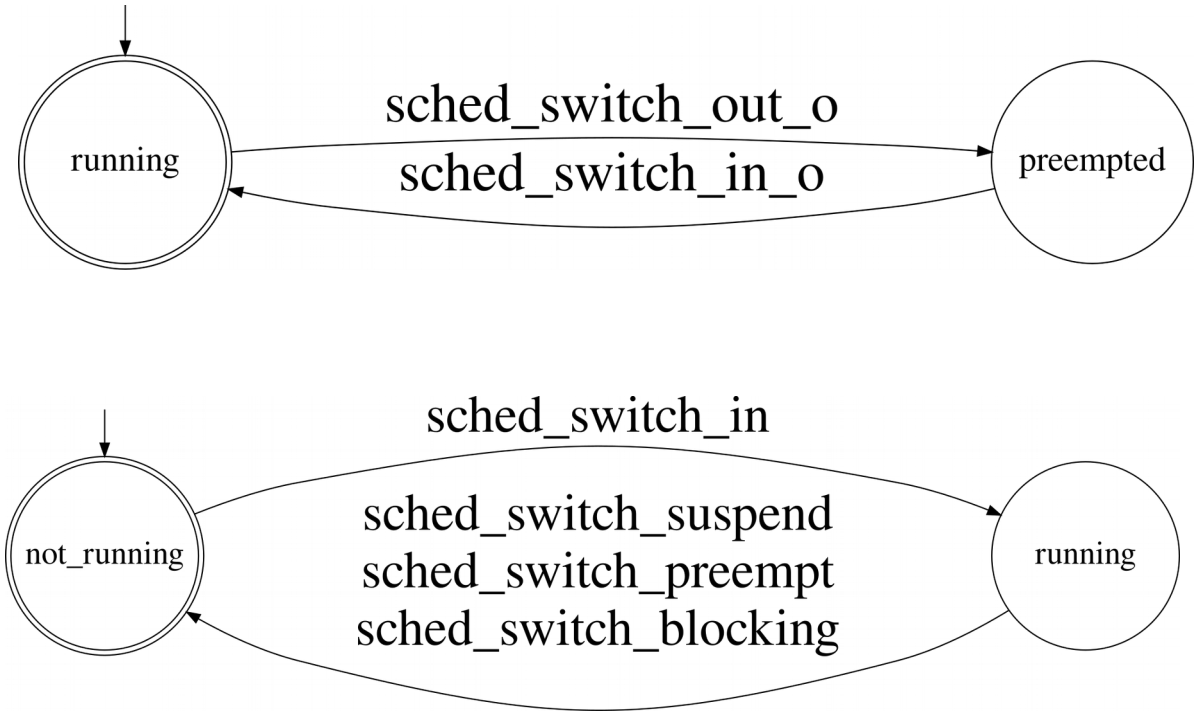
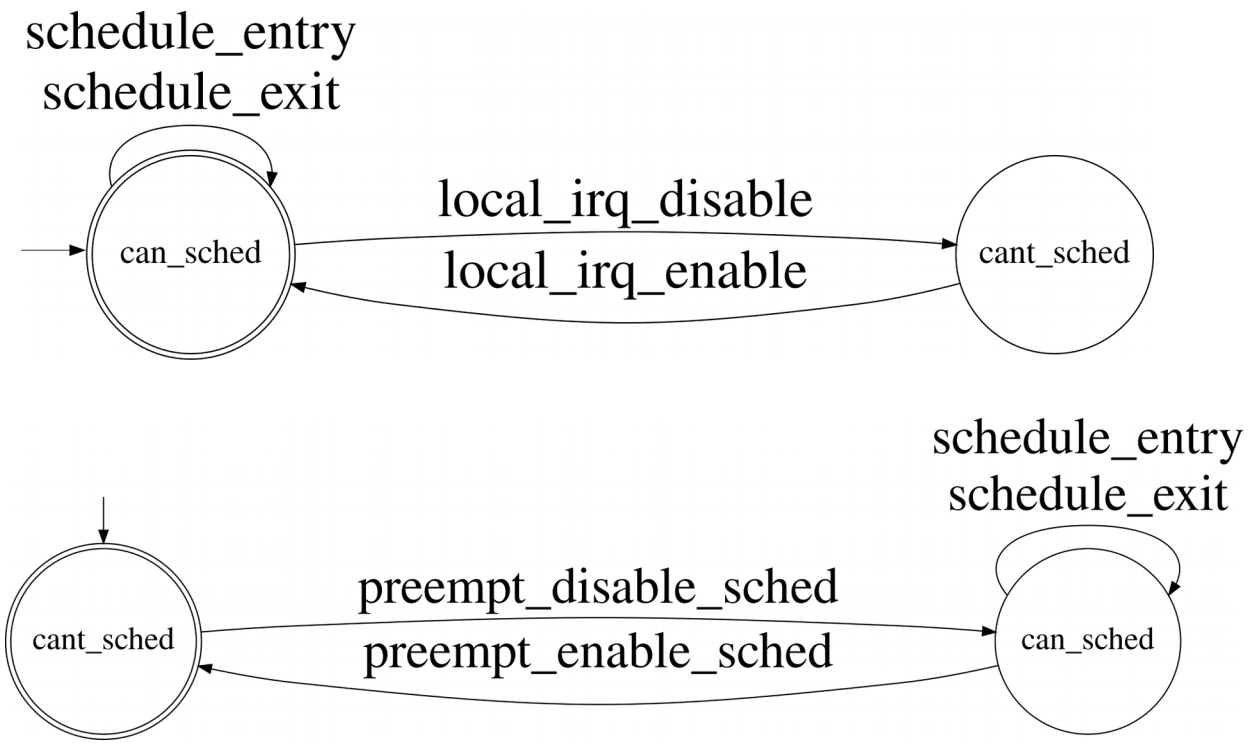
Independend “generators”



Necessary conditions



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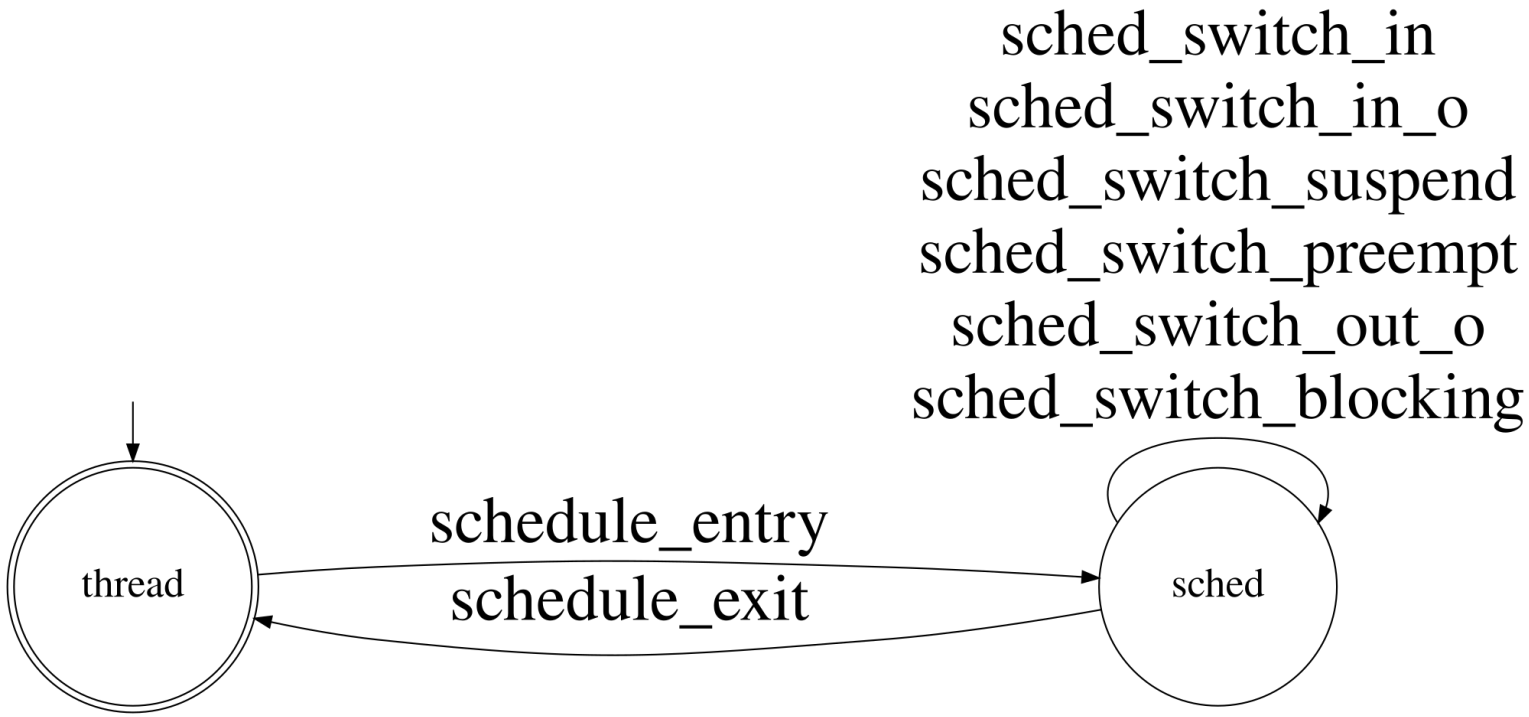
Necessary conditions



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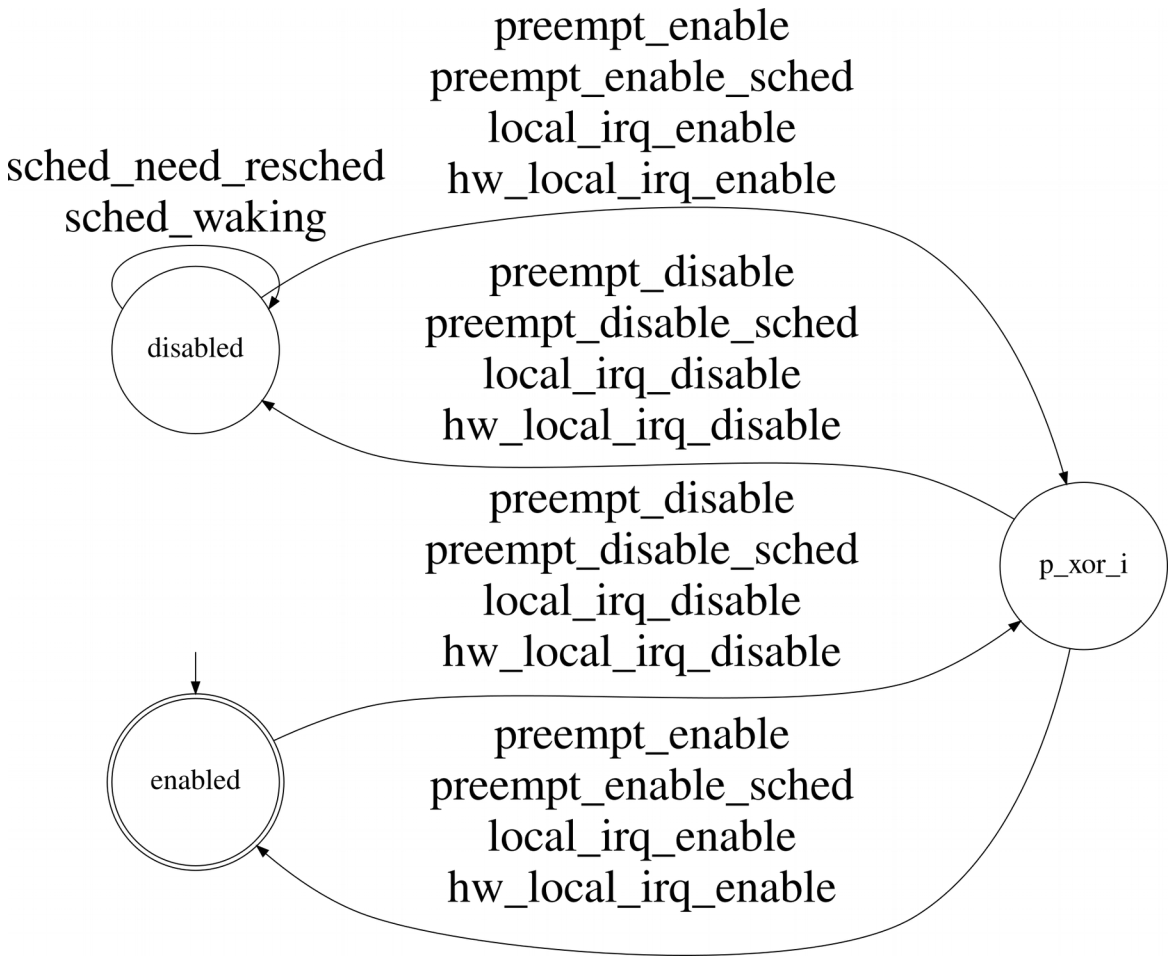
Necessary conditions



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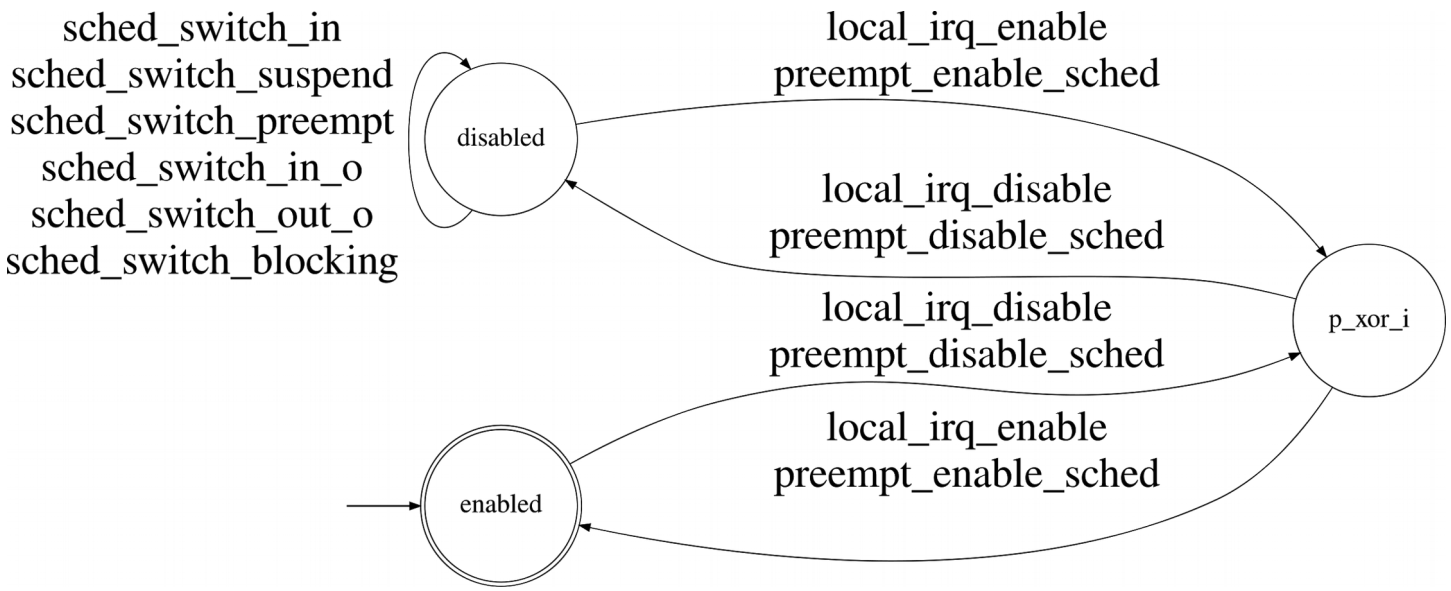
Necessary conditions



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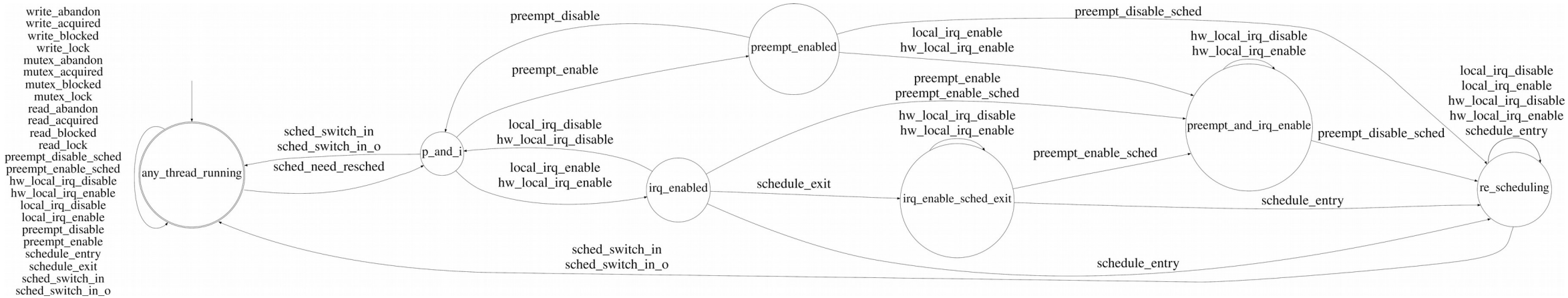
Sufficient conditions



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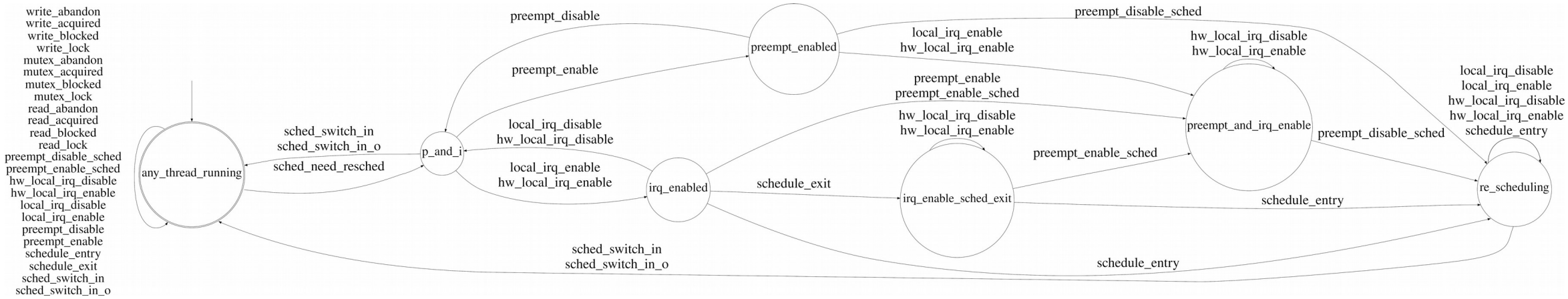
“PREEMPT”_RT is deterministic



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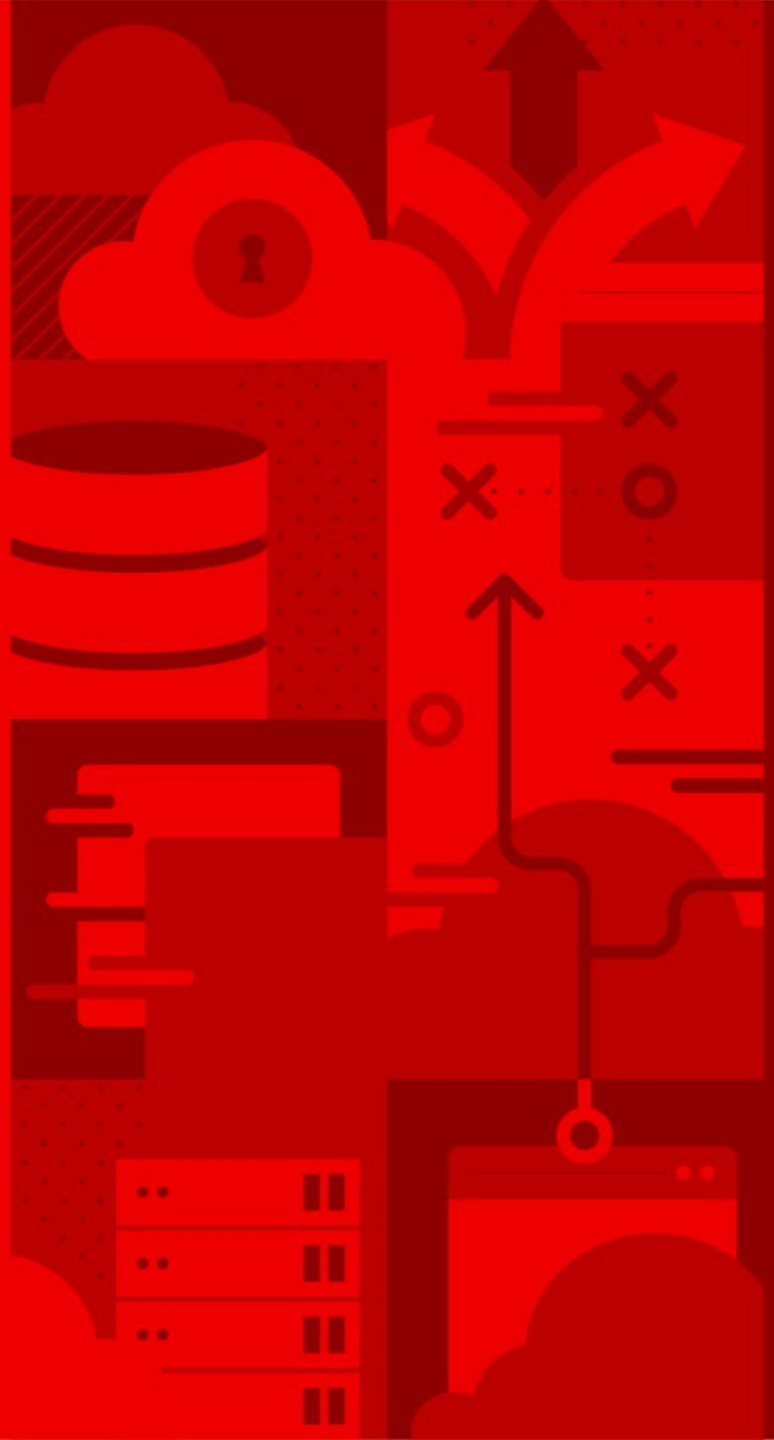
Academically accepted

Untangling the Intricacies of Thread Synchronization in the PREEMPT_RT Linux Kernel.
Daniel Bristot de Oliveira, Rômulo Silva de Oliveira & Tommaso Cucinotta
2019 IEEE 22nd International Symposium on Real-Time Distributed Computing (ISORC)

Modeling the Behavior of Threads in the PREEMPT_RT Linux Kernel Using Automata
Daniel Bristot de Oliveira, Tommaso Cucinotta & Romulo Silva De Oliveira
8th Embedded Operating Systems Workshop (EWiLi 2018)

Automata-Based Modeling of Interrupts in the Linux PREEMPT RT Kernel
Daniel Bristot de Oliveira, Rômulo Silva de Oliveira, Tommaso Cucinotta and Luca Abeni
Proceedings of the 22nd IEEE International Conference on Emerging Technologies And Factory Automation (ETFA 2017)



How to verify that the system _*behaves*_?

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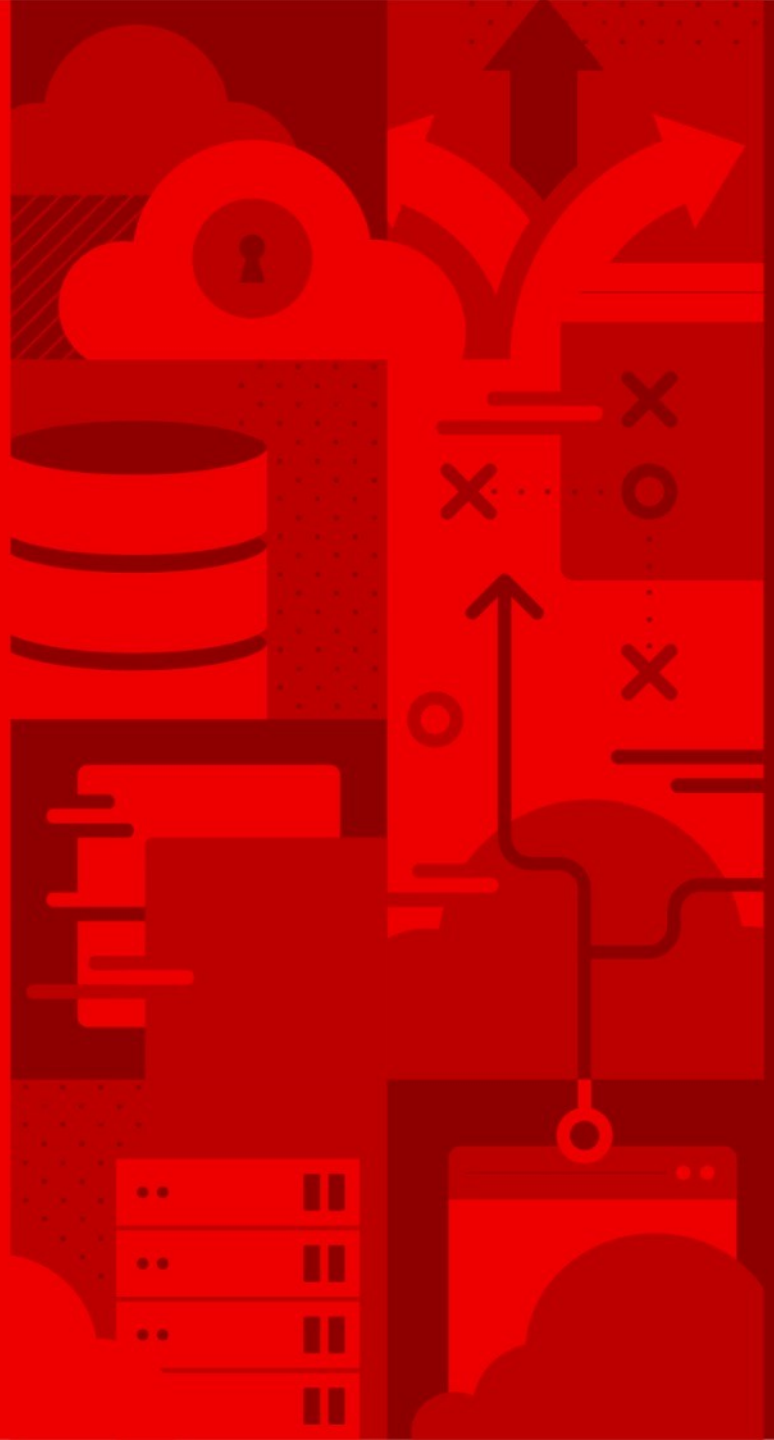

Comparing system execution against the model!

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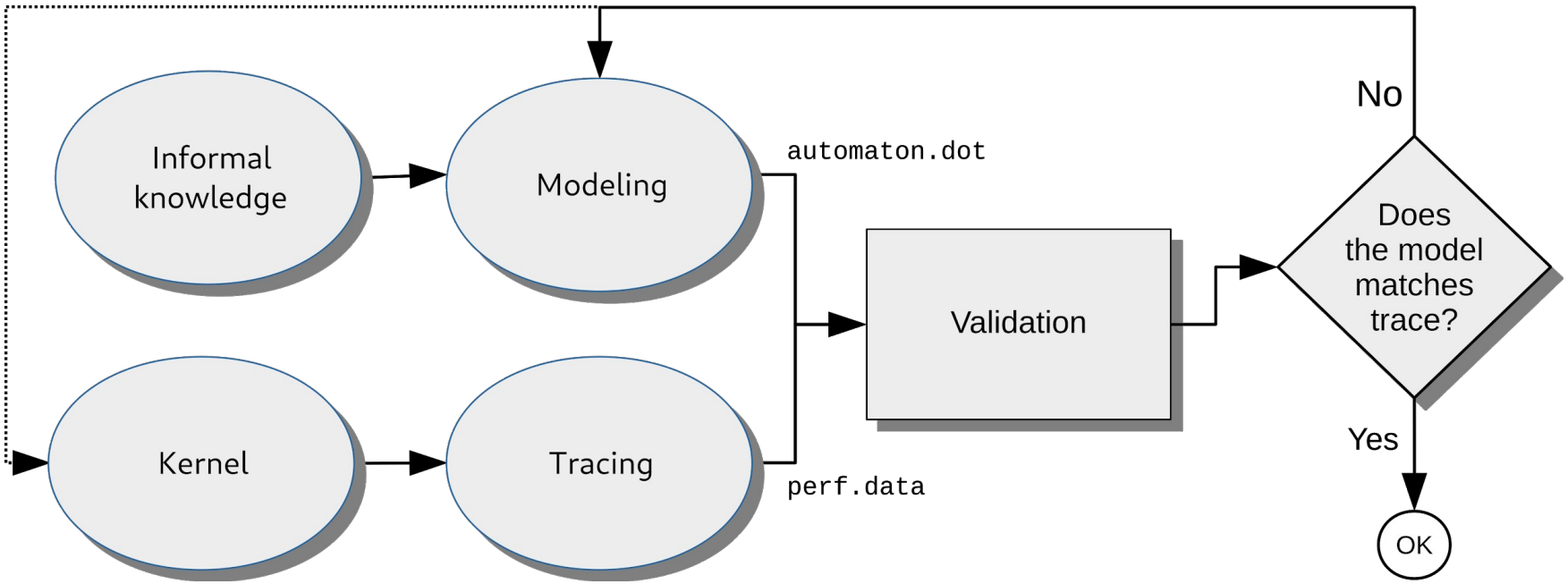
Offline & Asynchronous



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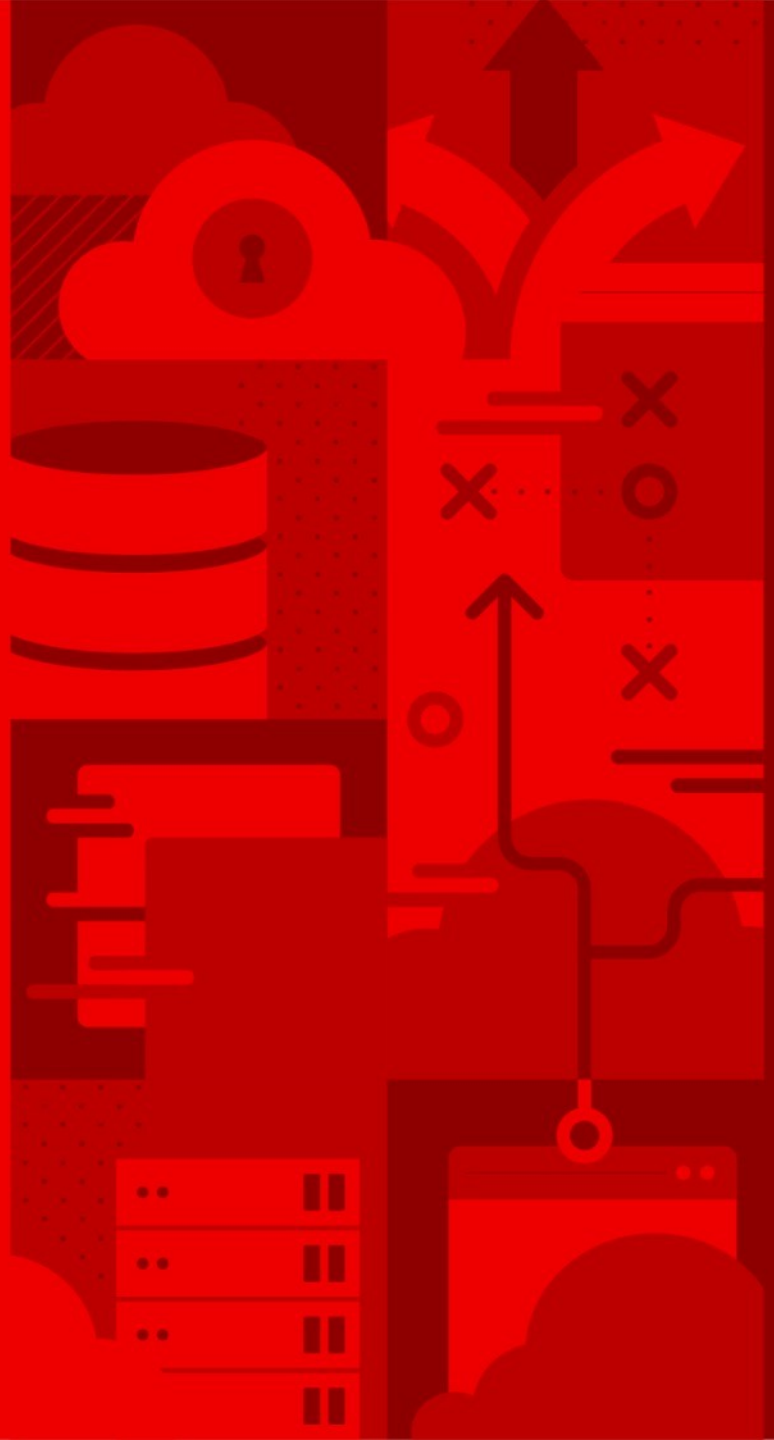
But...

Logical correctness for task model

- Example of patch catch'ed with the model
  - [PATCH RT] sched/core: Avoid__schedule() being called twice, the second in vain
- I am doing the model verification in user-space now:
  - Using perf + (sorry, peterz) tracepoints
  - It works, but requires a lot of memory/data transfer:
    - Single core, 30 seconds = 2.5 GB of data
    - We don't need all the data, only from a safe state to the problem.
  - It performs well, because the automata verification is O(1).
  - But still, the amount of data is massive.



What can we do?

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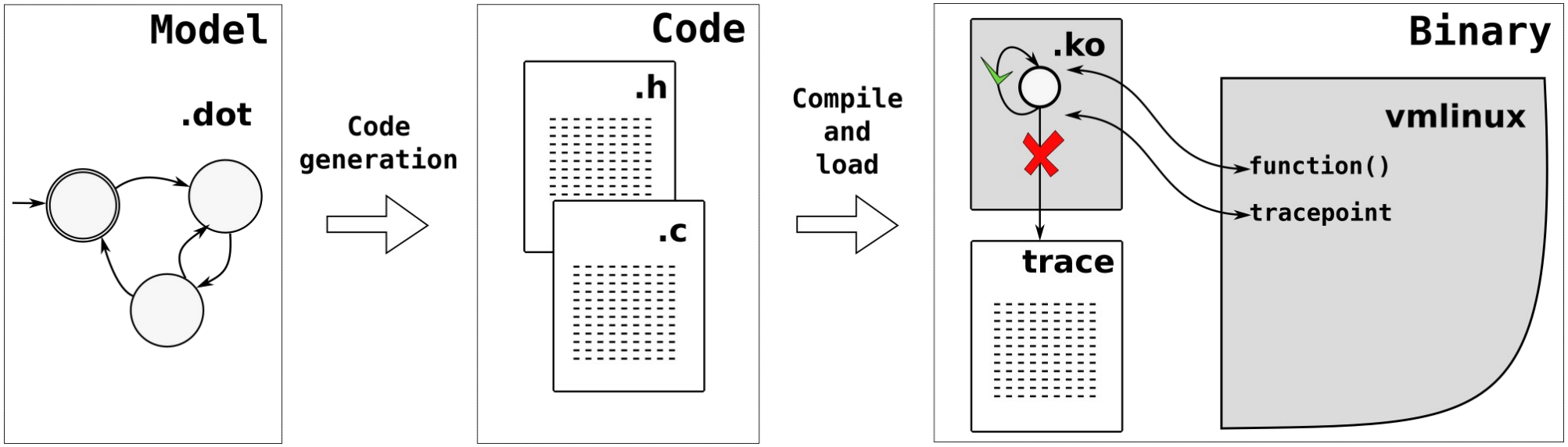
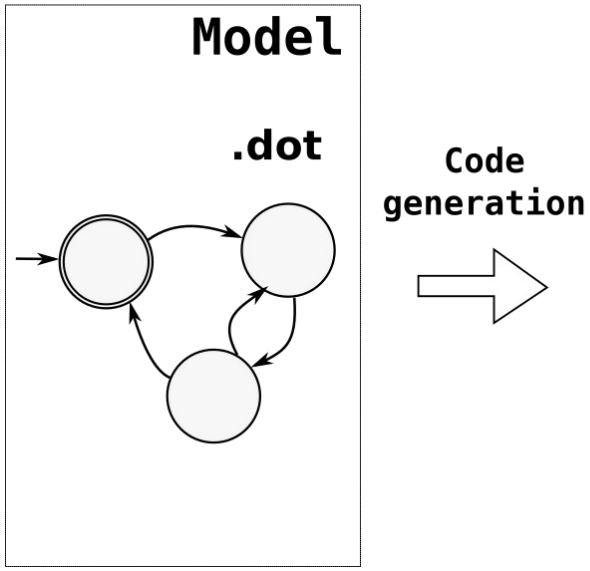
Online & Synchronous RV



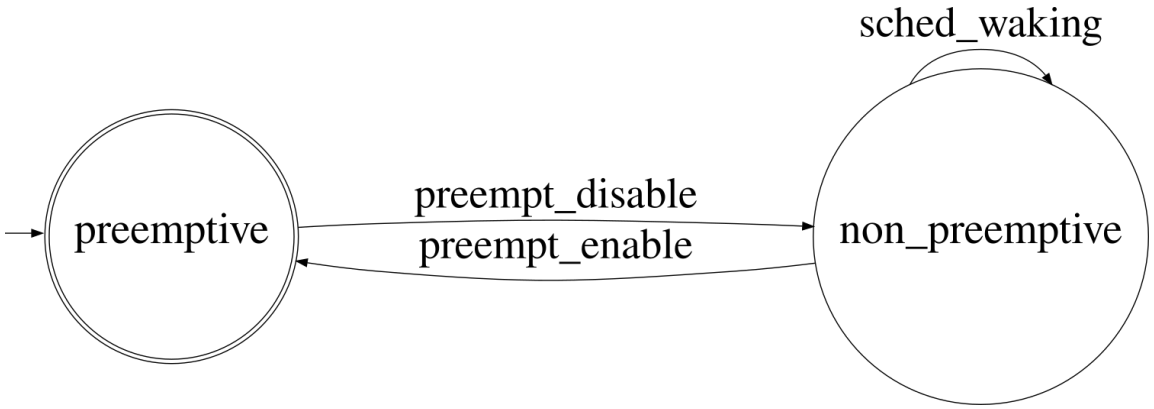
1) Code generation



- We develop the **dot2c** tool to translate the model into code
- It is a python program that has one input:
  - An automaton model in the **.dot** format
    - It is an open format (graphviz)
    - Supremica tool exports models with this format

Code generation

Wakeup in preemptive model:



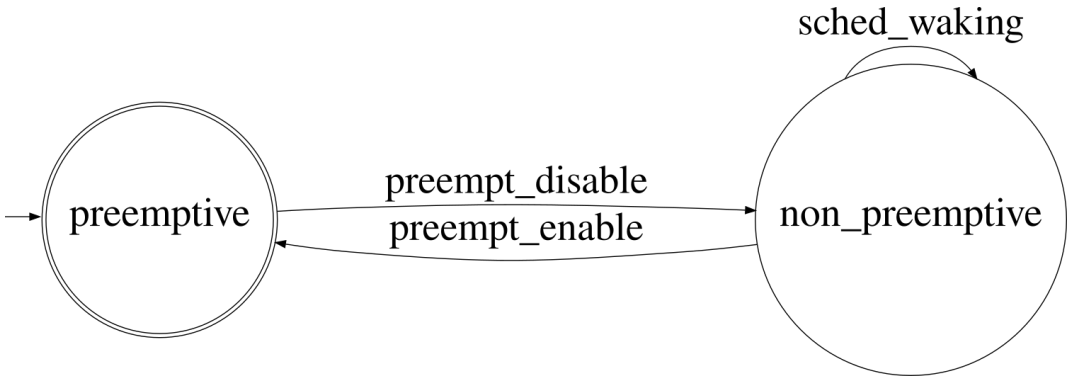
Code generation:

```
[bristot@t460s dot2c]$ ./dot2c wakeup_in_preemptive.dot
```

.....

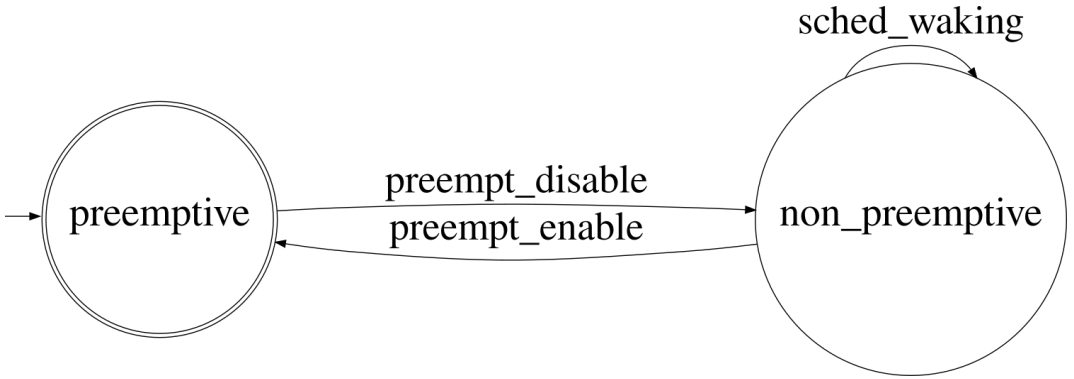
Automaton in C

```
enum states {
            preemptive = 0,
            non_preemptive,
            state_max
};

enum events {
            preempt_disable = 0,
            preempt_enable,
            sched_waking,
            event_max
};

struct automaton {
            char *state_names[state_max];
            char *event_names[event_max];
            char function[state_max][event_max];
            char initial_state;
            char final_states[state_max];
};
```



Automaton in C

```
enum states {
            preemptive = 0,
            non_preemptive,
            state_max
};

enum events {
            preempt_disable = 0,
            preempt_enable,
            sched_waking,
            event_max
};
....
struct automaton aut = {
            .event_names = { "preempt_disable", "preempt_enable", "sched_waking" },
            .state_names = { "preemptive", "non_preemptive" },
            .function = {
                        { non_preemptive,         -1,             -1 },
                        {             -1, preemptive, non_preemptive },
            },
            .initial_state = preemptive,
            .final_states = { 1, 0 }
};
```



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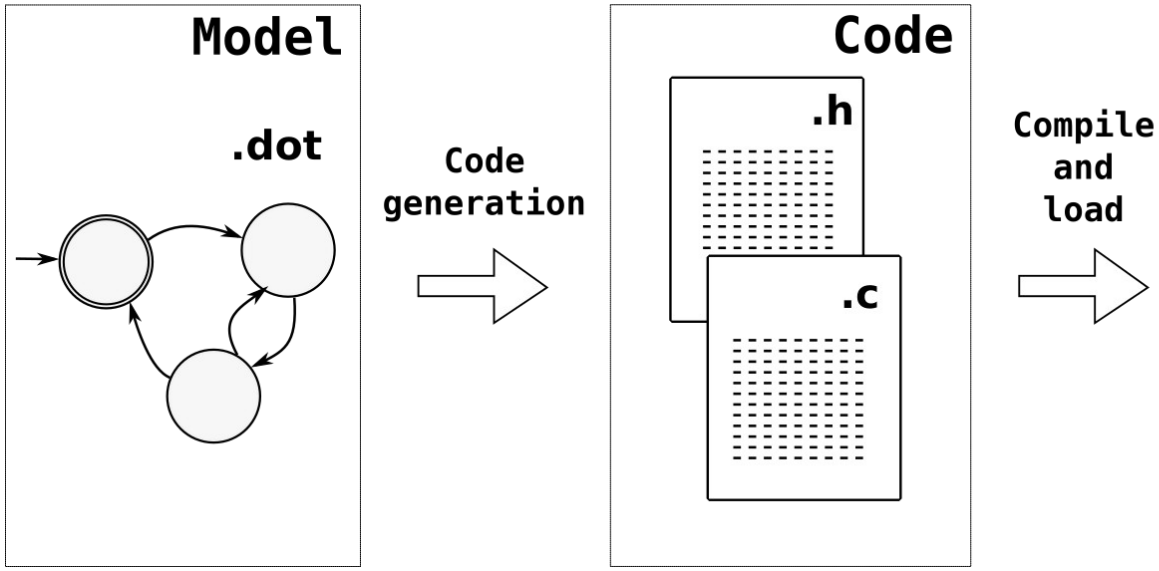
Processing functions



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Processing one event

```
char process_event(struct verification *ver, enum events event)
{
        int curr_state = get_curr_state(ver);
        int next_state = get_next_state(ver, curr_state, event);

        if (next_state >= 0) {
                set_curr_state(ver, next_state);

                debug("%s -> %s = %s %s\n",
                        get_state_name(ver, curr_state),
                        get_event_name(ver, event),
                        get_state_name(ver, next_state),
                        next_state ? "" : "safe!");

                return true;
        }

        error("event %s not expected in the state %s\n",
                get_event_name(ver, event),
                get_state_name(ver, curr_state));

        stack(0);

        return false;
}
```

Processing one event

```
char *get_state_name(struct verification *ver, enum states state)
{
            return ver->aut->state_names[state];
}

char *get_event_name(struct verification *ver, enum events event)
{
            return ver->aut->event_names[event];
}

char get_next_state(struct verification *ver, enum states curr_state, enum events event)
{
            return ver->aut->function[curr_state][event];
}

char get_curr_state(struct verification *ver)
{
            return ver->curr_state;

}

void set_curr_state(struct verification *ver, enum states state)
{
            ver->curr_state = state;
}
```

Processing one event

```
char *get_state_name(struct verification *ver, enum states state)
{
            return ver->aut->state_names[state];
}

char *get_event_name(struct verification *ver, enum events event)
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char get_next_state(struct verification *ver, enum states curr_state, enum events event)
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            return ver->aut->function[curr_state][event];
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char get_curr_state(struct verification *ver)
{
            return ver->curr_state;

}

void set_curr_state(struct verification *ver, enum states state)
{
            ver->curr_state = state;
}
```
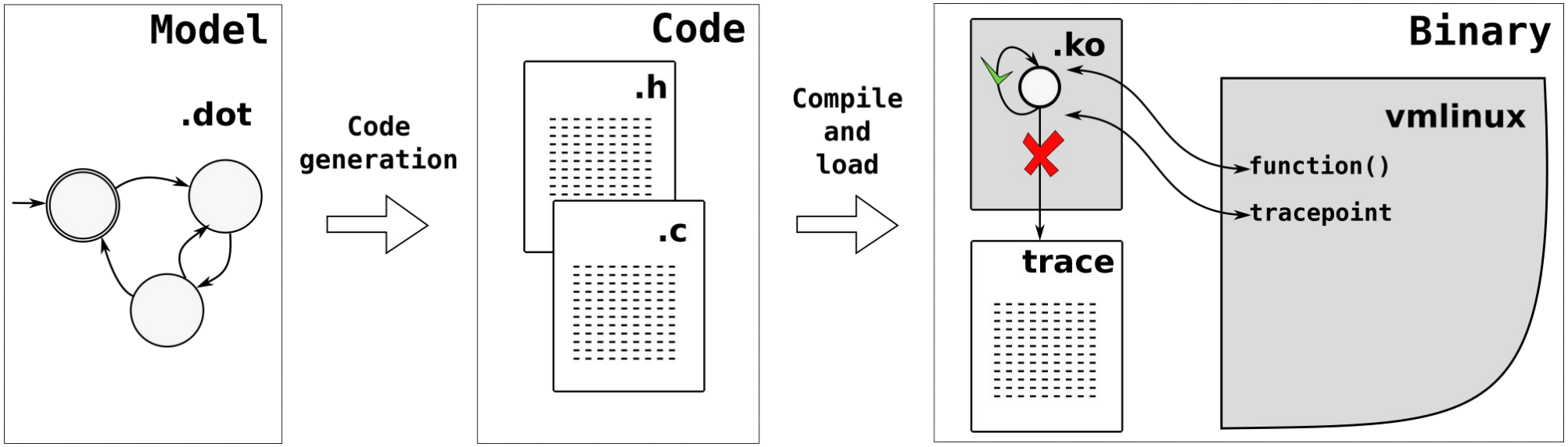

All operations are O(1)!

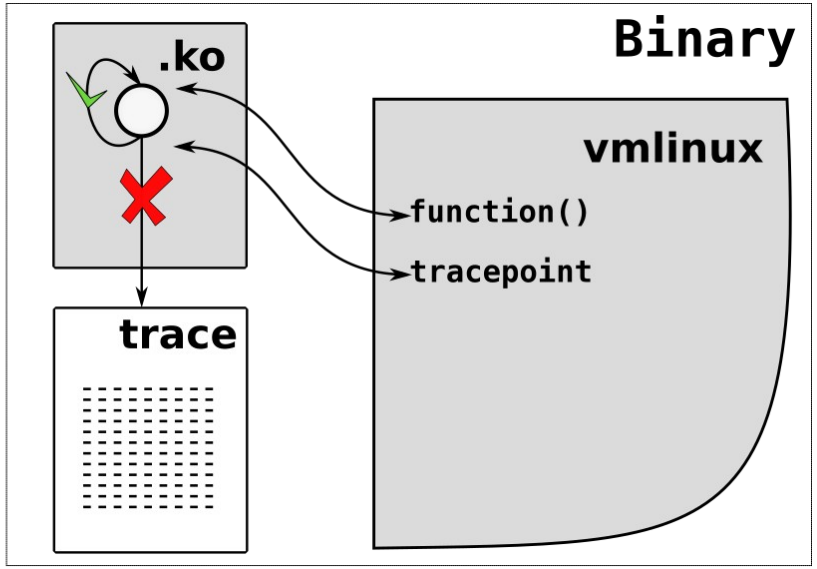
Only one variable to keep the state!

3) Verification



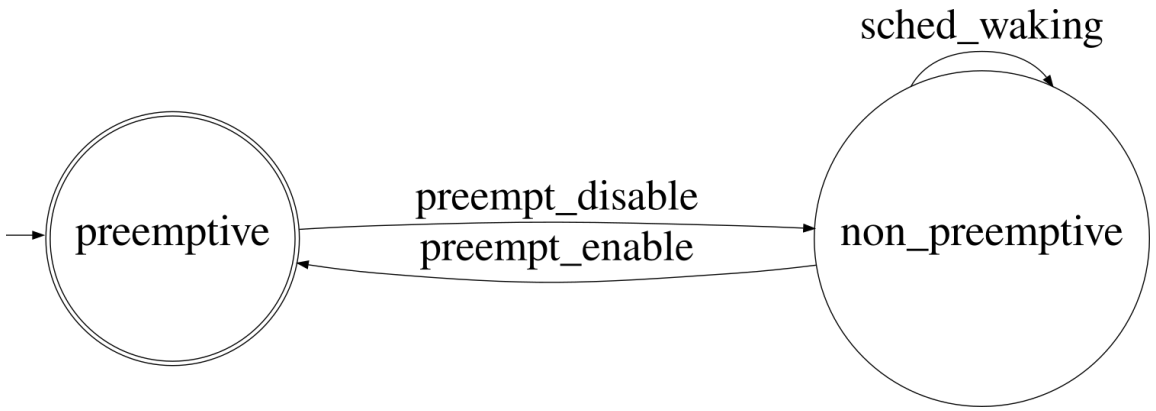
Verification

- Verification code is compiled as a kernel module
- Kernel module is loaded to a running kernel
  - While no problem is found:
    - Either print all event's execution
    - Or run silently
- If an unexpected transitions is found:
  - Print the error on trace buffer



Error output

```
bash-1157  [003] ....2..   191.199172: process_event: non_preemptive -> preempt_enable = preemptive safe!
bash-1157  [003] dN..5..   191.199182: process_event: event sched_waking not expected in the state preemptive
bash-1157  [003] dN..5..   191.199186: <stack trace>
=> process_event
=> __handle_event
=> ttwu_do_wakeup
=> try_to_wake_up
=> irq_exit
=> smp_apic_timer_interrupt
=> apic_timer_interrupt
=> rcu_irq_exit_irqson
=> trace_preempt_on
=> preempt_count_sub
=> _raw_spin_unlock_irqrestore
=> __down_write_common
=> anon_vma_clone
=> anon_vma_fork
=> copy_process.part.42
=> _do_fork
=> do_syscall_64
=> entry_SYSCALL_64_after_hwframe
```



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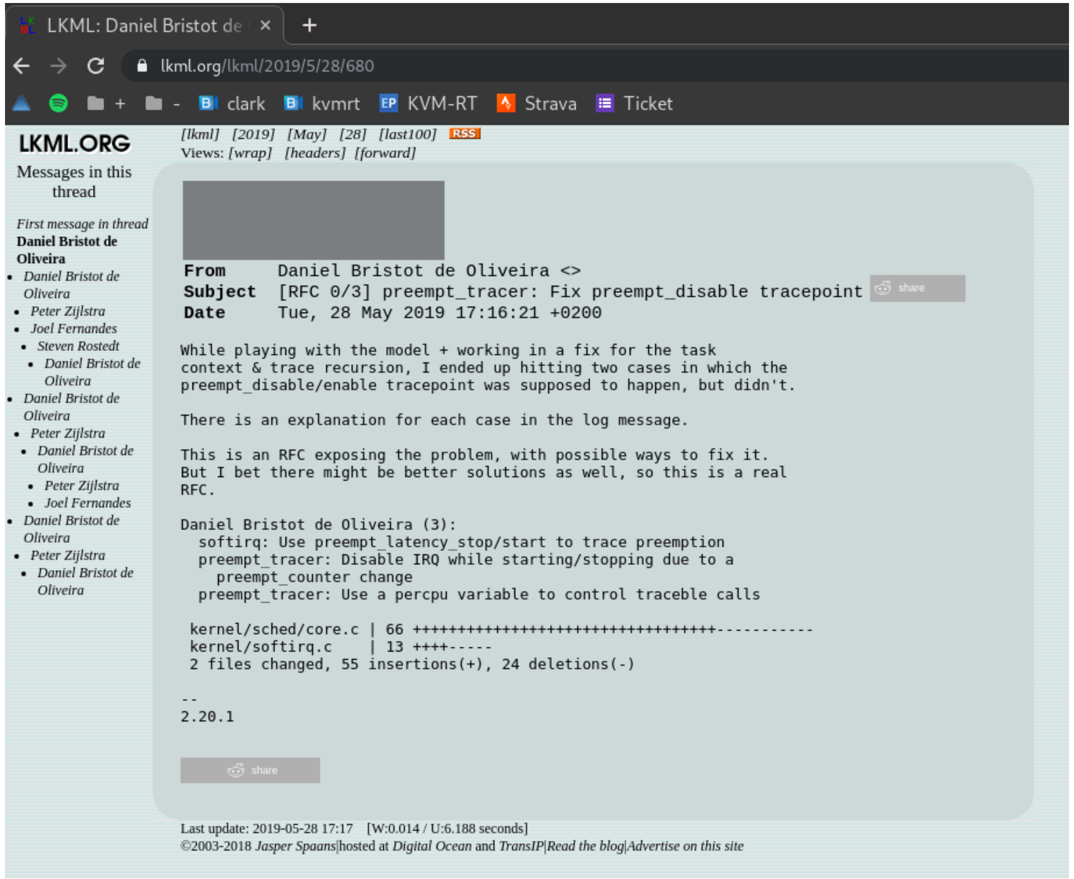
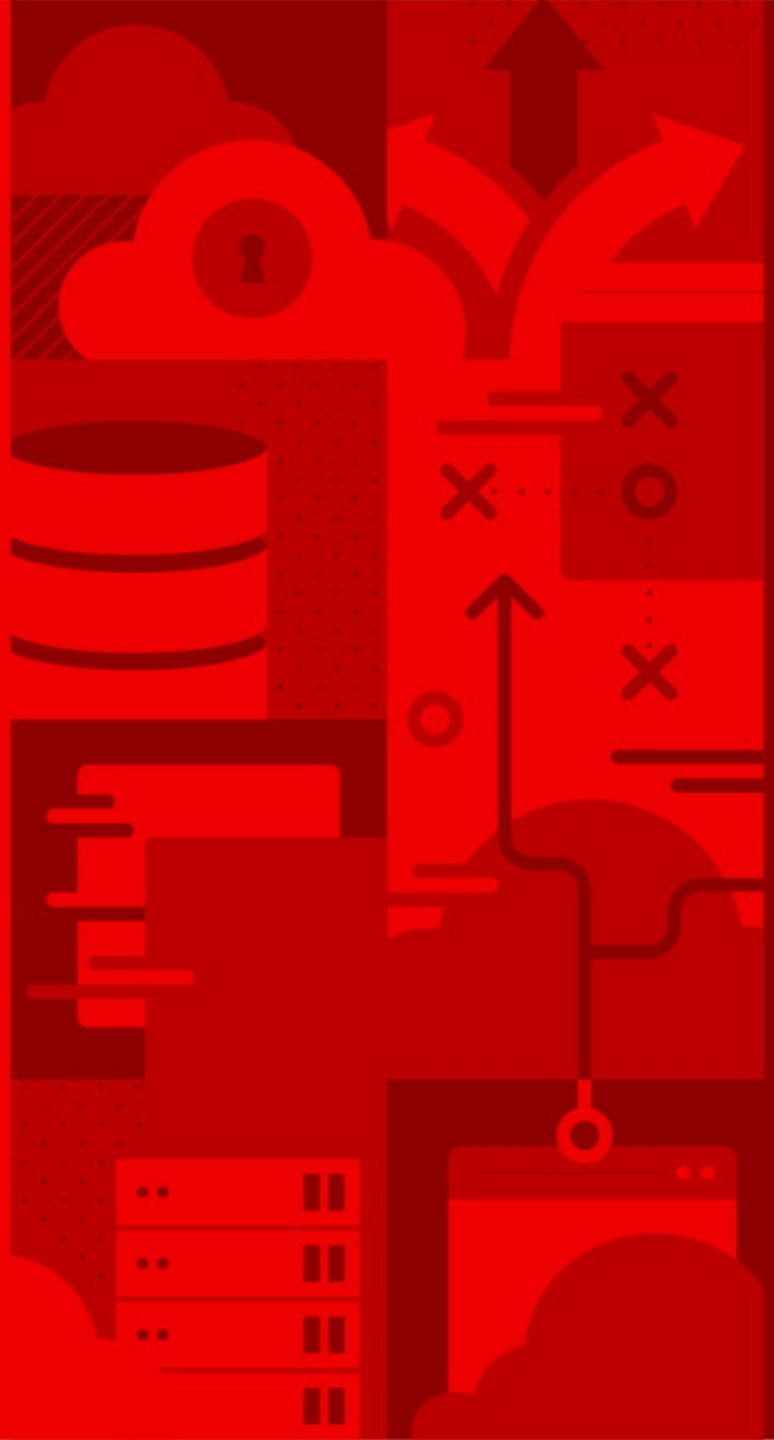
Practical example

- A problem with tracing subsystem was reported using this model's module
  - https://lkml.org/lkml/2019/5/28/680

    <recall to open the link>





There is not free meal!

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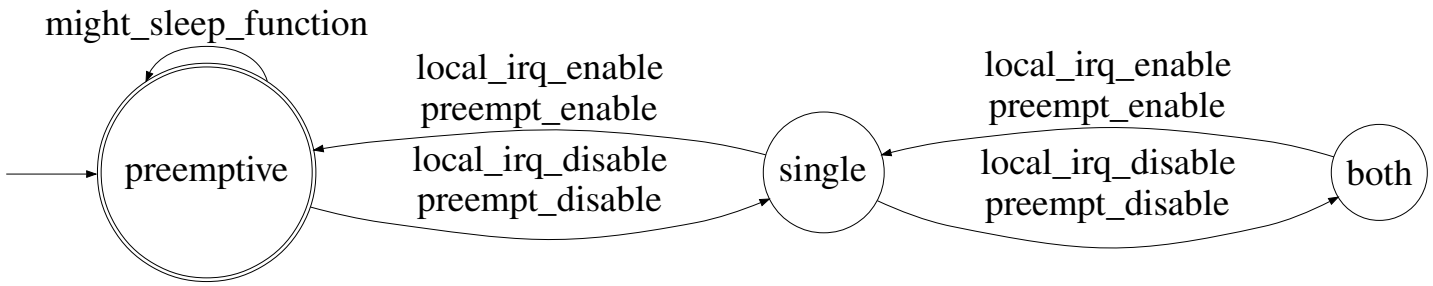
The price is in the data structure

- The vectors and matrix are not “compact” data structure
- BUT!
- The PREEEMPT_RT model, with:
  - 9017 states!
  - 23103 transitions!
  - Compiles in a module with < 800KB
  - **Acceptable, no?**

In practice... also..

- Complete models like the PREEMPT_RT are not necessarily need.
- Small models can be created as “test cases”
- For example:



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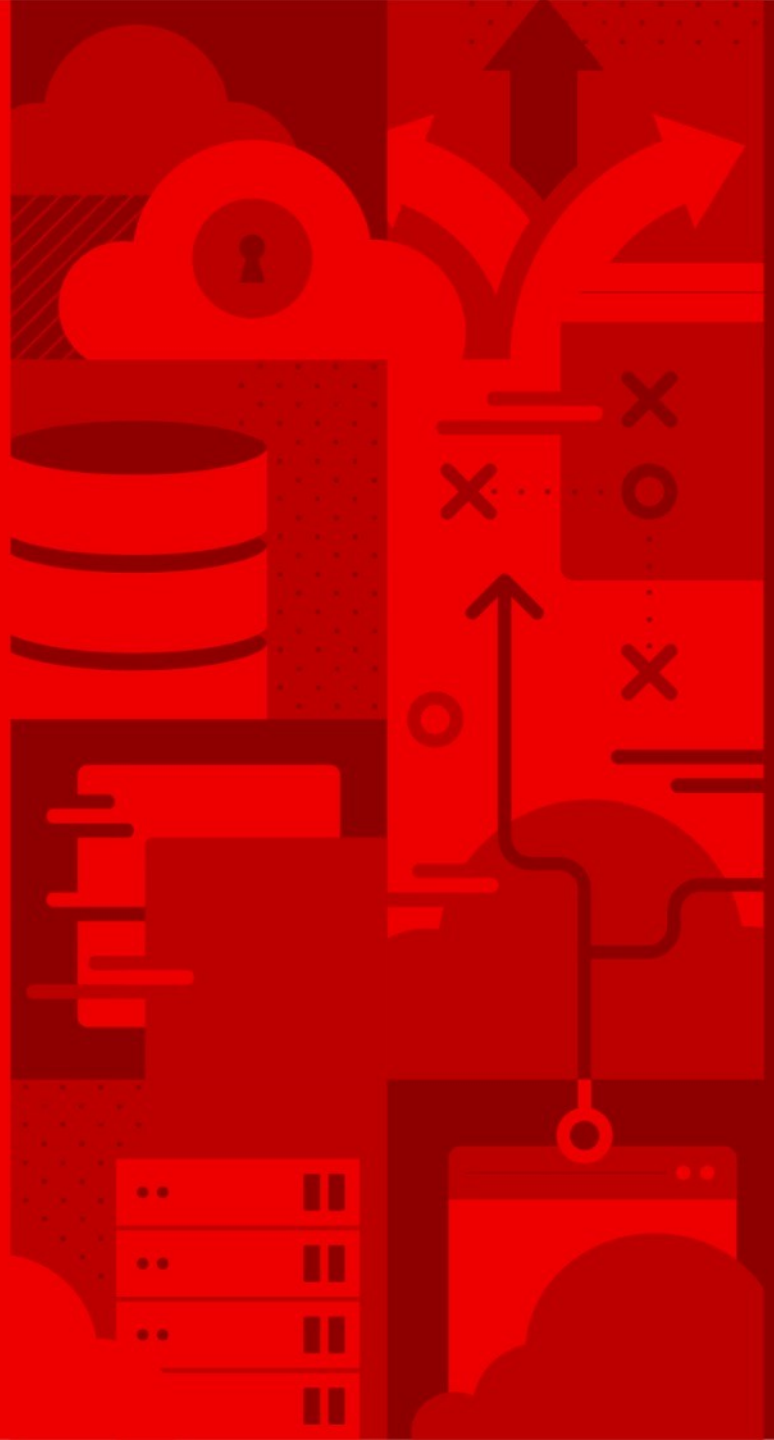

How _*efficient*_ is this idea?

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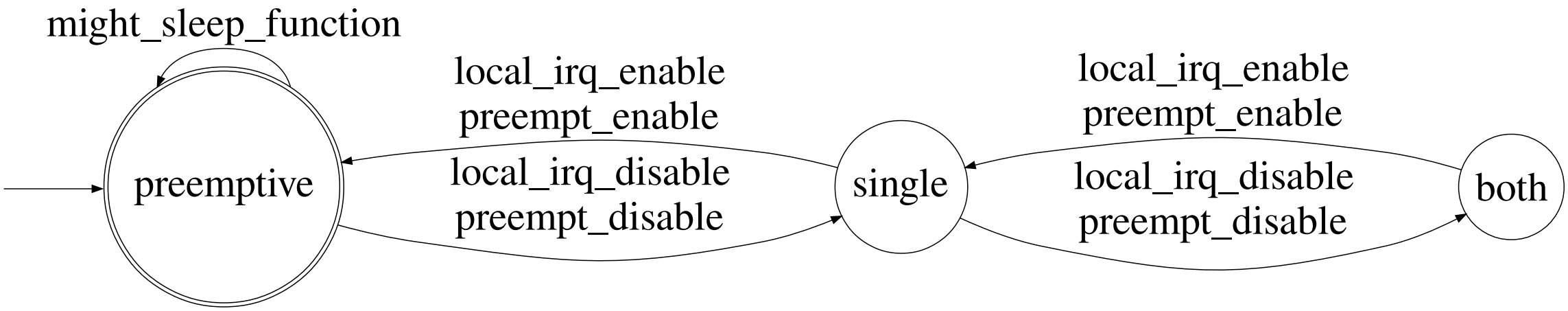
Efficiency in practice: a benchmark

- Two benchmarks
  - Throughput: Using the Phoronix Test Suite
  - Latency: Using cyclictest
- Base of comparison:
  - **as-is**: The system without any verification or trace.
  - **trace**: Tracing (ftrace) the same events used in the verification
    - Only trace! No collection or interpretation.

Throughput: SWA model



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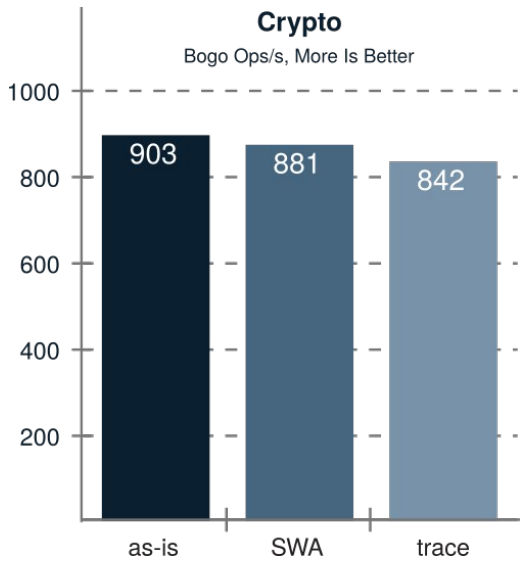
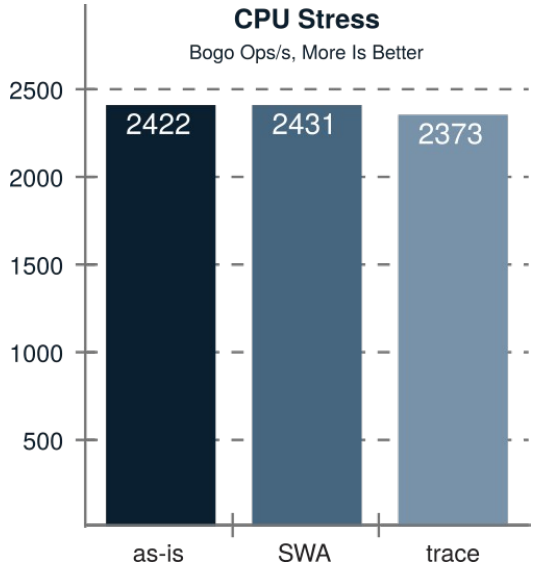
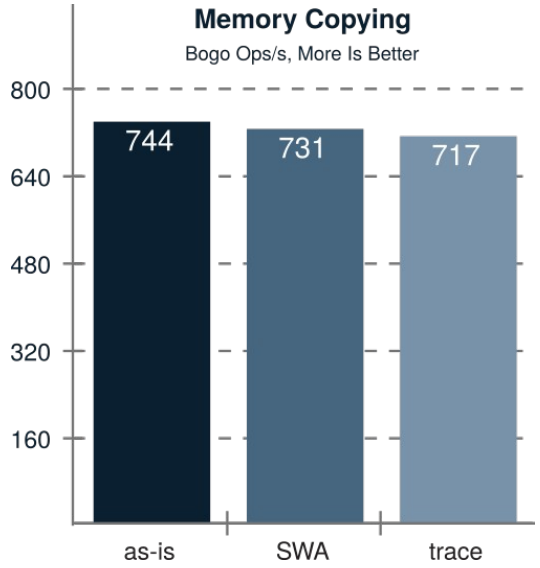
Benchmark: Thoughput – Low kernel activation







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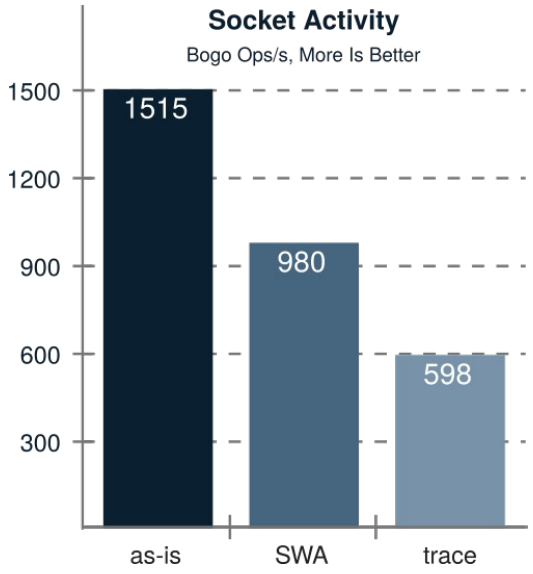
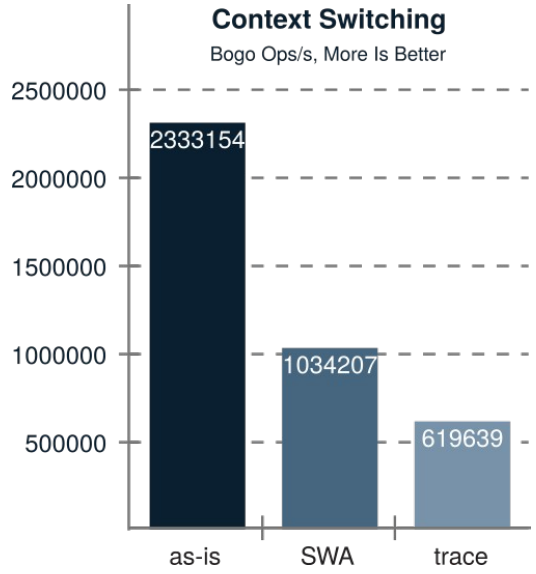
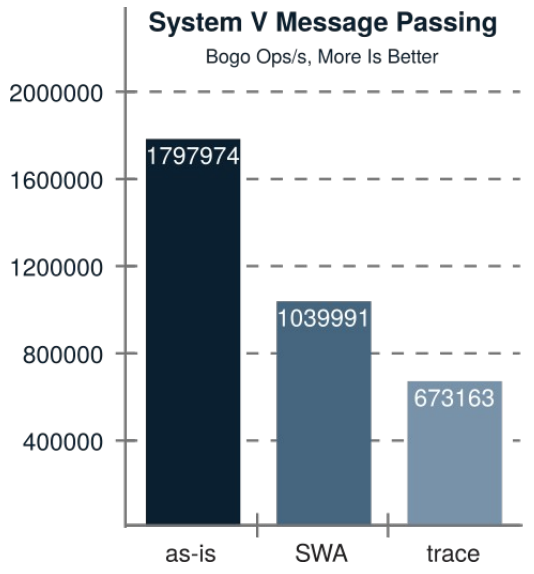
Benchmark: Thoughput – High kernel activation







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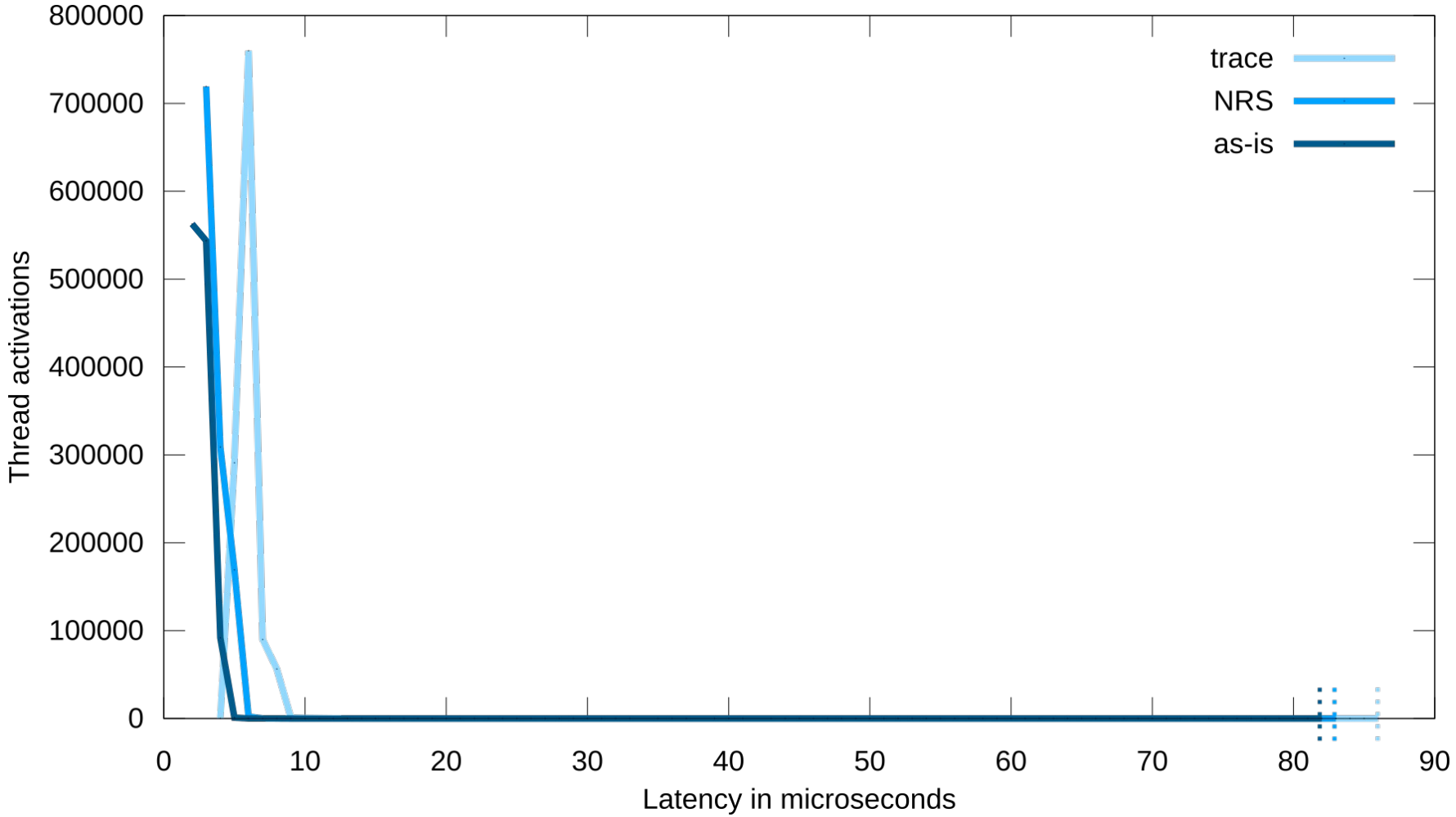
Benchmark: Cyclictest latency



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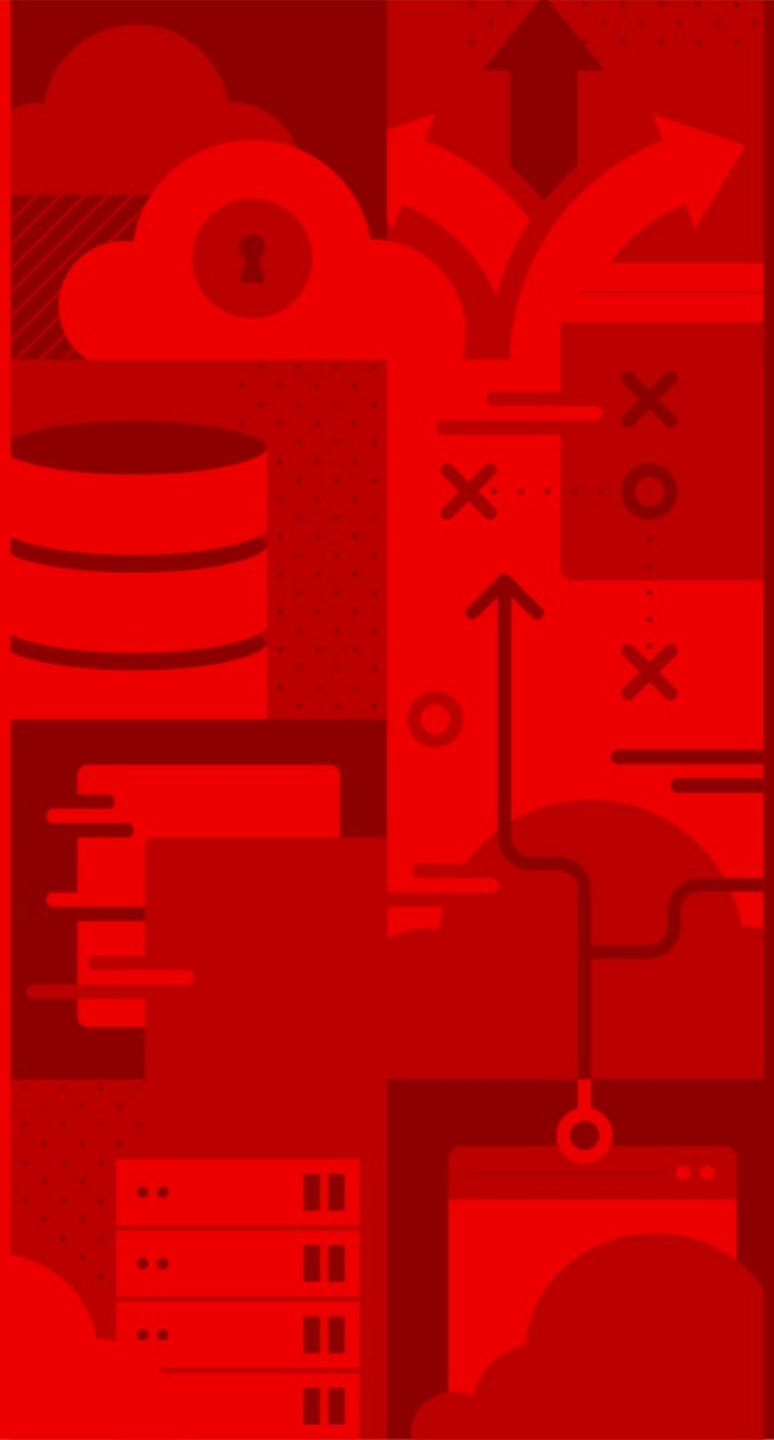
Academically accepted

Efficient Formal Verification for the Linux Kernel

Daniel Bristot de Oliveira, Rômulo Silva de Oliveira & Tommaso Cucinotta

17th International Conference on Software Engineering and Formal Methods (SEFM)

More info here: http://bristot.me/efficient-formal-verification-for-the-linux-kernel/



So…

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So...

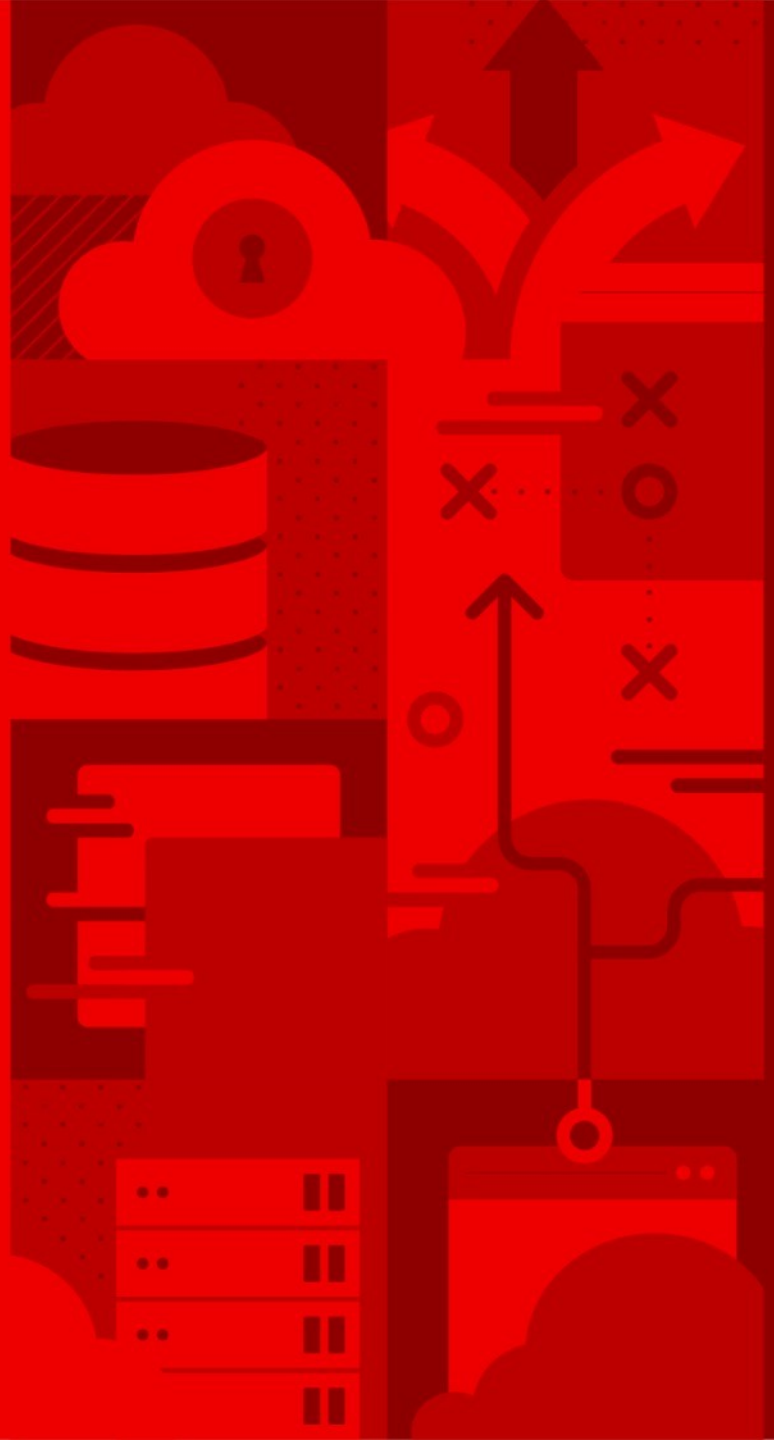
- It is possible to model complex behavior of Linux
  - Using a formal language
  - Creating big models from small ones
- It is possible to verify properties of models
  - And so properties of the system
  - Bonus: It is possible to use other more complex methods by using the automata
    - LTL and so on
- It is possible to verify the runtime behavior of Linux

What's next?

- Better interface
  - Working in a perf/ebpf version of the runtime verification part
  - And also working with a "ftrace" like interface
  - Then I will compare both
- Documenting the process in a "linux developer way"
  - IOW: translating the papers into LWN articles

What should we model?

- There are other possible things to model
  - Locking (part of lockdep)
    - Why?
    - Run-time without recompile/reboot.
  - RCU?
  - Schedulers?



Worth Mentioning

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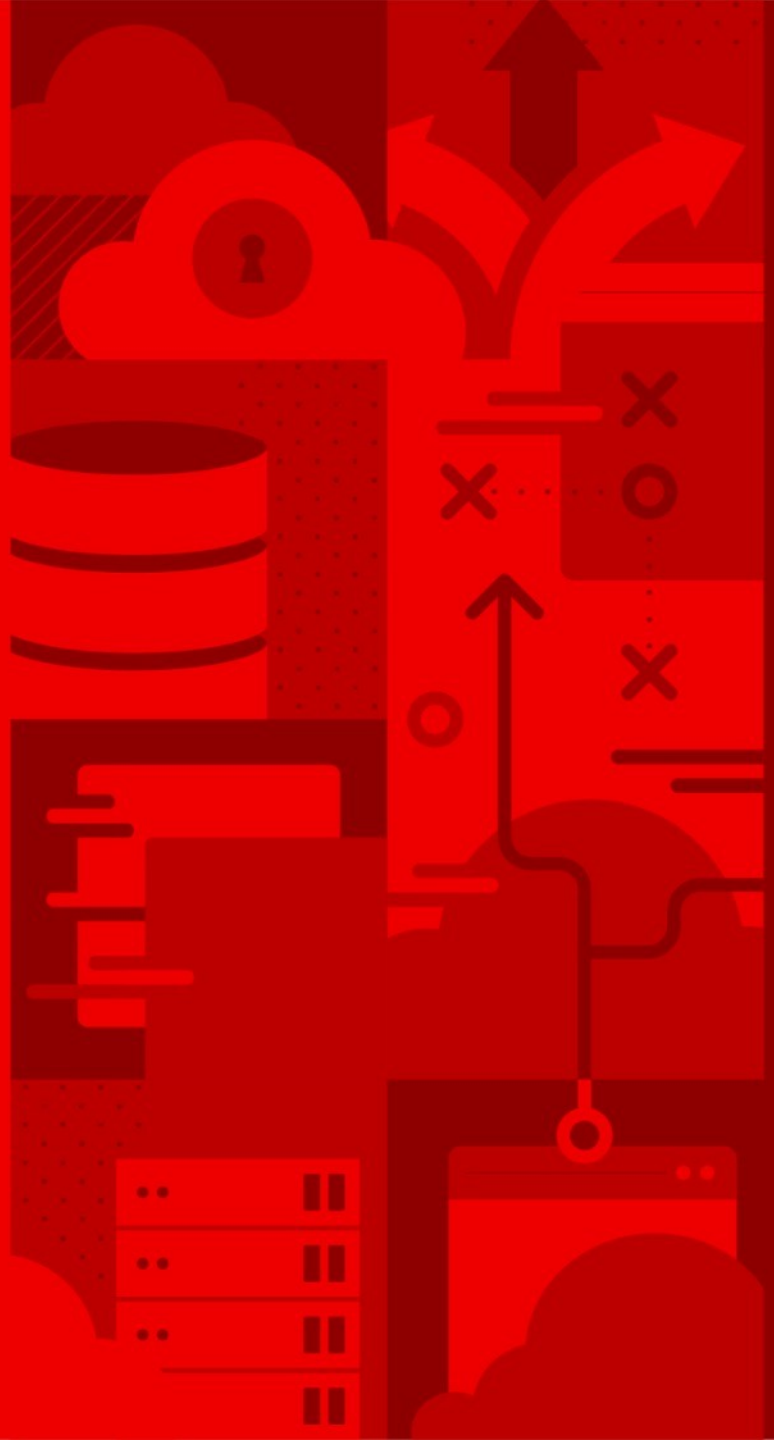

Something else?

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Thank you!

This work is made in collaboration with:

the Retis Lab @ Scuola Superiore Sant'Anna (Pisa – Italy)

Universidade Federal de Santa Catarina (Florianópolis - Brazil)

Red Hat