Red Hat Enterprise Linux

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Efficient Formal Verification for the Linux kernel

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Linux and Formal methods

- Linux has been used on many **safety-critical** and/or **real-time systems**
  - From **sensor networks** and **robotics**
  - To control of military **drones** and **high-frequency trading** systems
- Formal **verification of Linux is a non-negotiable requirement** for next-generation of cyber-physical systems, e.g., self-driven cars.

Linux and Formal methods

- The need fomented the application of formal models for Linux.
- Previous work using automata-based models has shown to be practical for Linux developers.
  - Because of the rich tracing features already present on kernel...
  - Linux is already analyzed as a ***Discrete Event System*** by practitioners
- However, Linux lacks a methodology for runtime verification that can be applied broadly throughout all of the in-kernel subsystems, efficiently.
  - And the **Linux kernel community has shown the desire of exploring such possibility.**

Paper contributions

Contributions

- This paper proposes an **efficient automata-based runtime verification method** for the Linux kernel
  - Verifying the correct sequences of in-kernel events as happening at runtime, against an automata-based model that has been previously created
- Presents an **automatic code generation tool** for automata-based models
  - Takes the advantage of the in-kernel tracing infrastructure to dynamically enable runtime control of the verification
- Presents a performance evaluation of the verification method

Background

Linux Tracing

- Linux has an advanced set of tracing methods, including:
  - Tracing of Kernel functions (call and return)
  - Tracepoints: specific points in the code
  - Dynamic tracepoints: tracepoints dynamically added to a running kernel
  - And more
- Trace example:

```
sh-2038  [002] d... 16230.043339: ttwu_do_wakeup ←try_to_wake_up
sh-2038  [002] d... 16230.043339: check_preempt_curr <-ttwu_do_wakeup
sh-2038  [002] d... 16230.043340: resched_curr <-check_preempt_curr
sh-2038  [002] d... 16230.043343: sched_wakeup: comm=cat pid=2040 prio=120 target_cpu=003
```

Linux Tracing

- **Tracing** code call **is not hard-coded** on Linux
  - At boot time, all the **tracing calls are** transformed into **no-op**
    - *Almost no overhead at runtime*
    - *It is enabled on the vast majority of Linux distros*
  - At runtime, when enabling tracing, **no-op are transformed into calls to trace functions**
- More than one **tracer function can *hook* to an trace call**, dynamically
  - **Live Patching** uses trace hooks to intercept a *bad function* call, deviating it to a *good one*
  - Available for other methods as well, including modules

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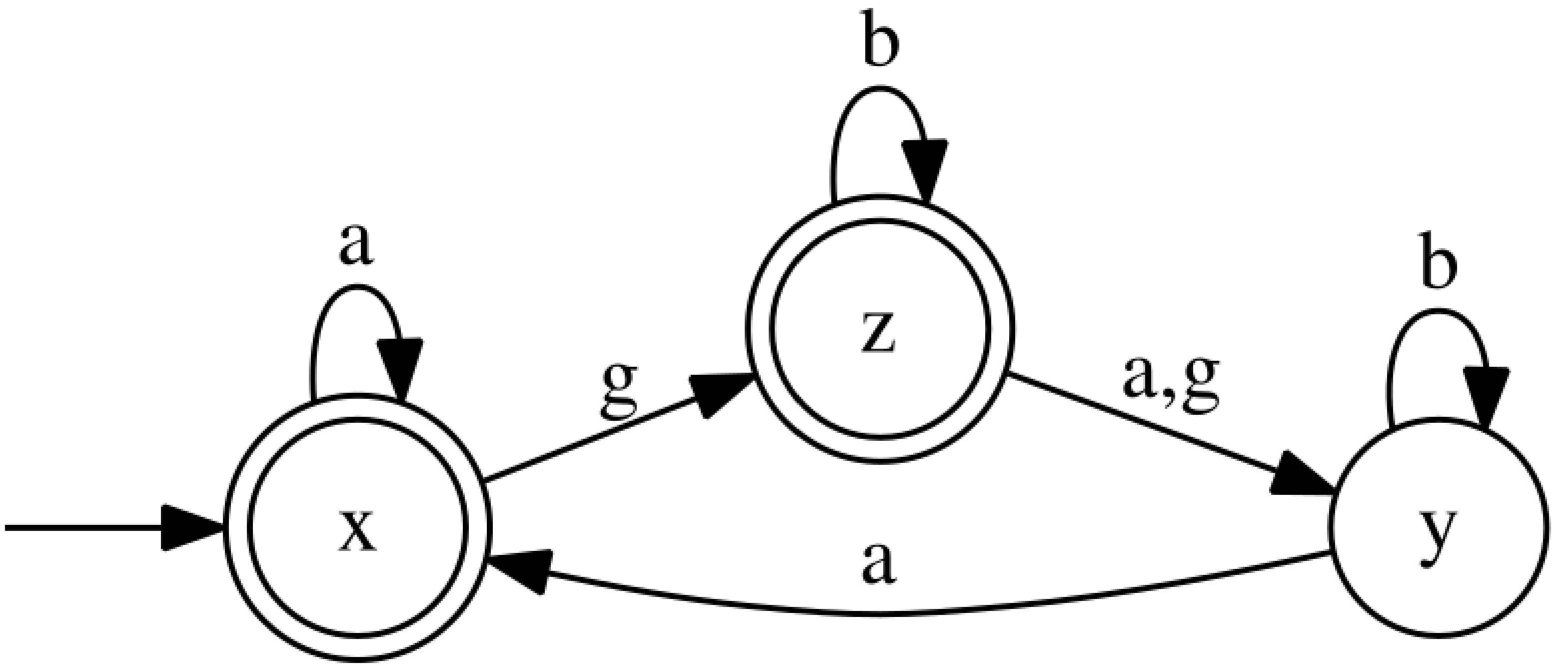
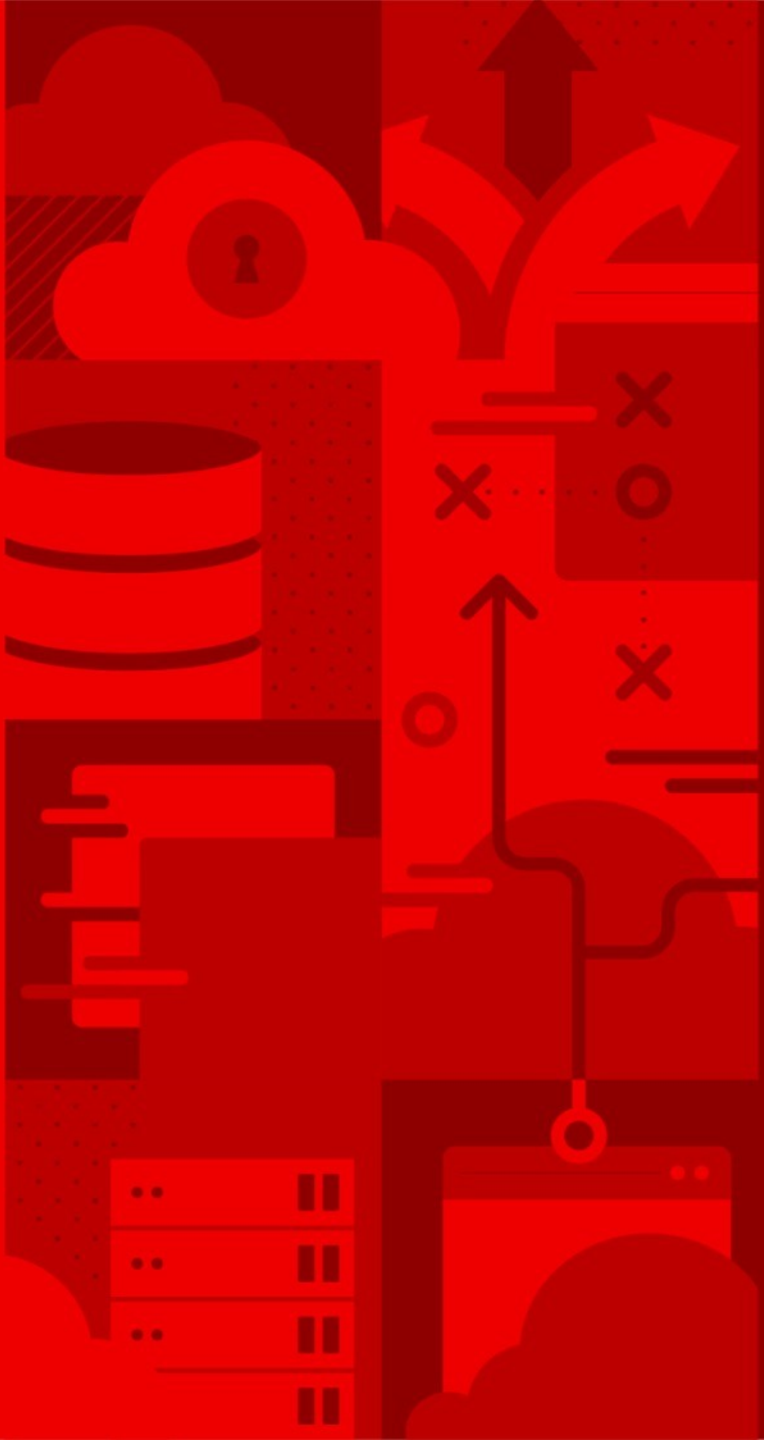
Automata and DES

- Automata is a method to model **Discrete Event Systems** (DES)
  - Formally, an automaton is defined as:
    - $G = \{ X, E, f, x_0, X_m \}$, where:
      - X = finite set of states;
      - E = finite set of events;
      - f = 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 and DES





Related work

FM and OS kernels

- **BLAST** tool uses control flow automata, along with techniques for state-space reduction, applied to the verification of safety properties of OS drivers for the **Linux** and Microsoft Windows NT kernels.
    - Henzinger, Jhala, Majumdar, and Sutre (2002)
- **SLAM** static code analyzer, enabling C programs to be analyzed to detect violations of certain conditions. Also used within the Static Driver Verifier (SDV) framework to check Microsoft Windows device drivers against a set of rules.
    - Ball, Rajamani, (2002)
- **MAGIC**, a tool for automatic verification of sequential C programs against finite state machine specifications.
    - Chaki, Clarke, Groce, Jha, and Veith (2004)
    - **MAGIC** has been used to verify locking correctness (deadlock-freedom) in the **Linux** kernel.

FM and Linux Community

- **Lockdep** is in-kernel tool able to identify errors in the use of locking primitives that could eventually lead to deadlocks.
- **Linux Kernel Memory Consistency Model** (LKMM) subsystem, is an array of tools that formally describe the Linux memory consistency model, and also producing “litmus tests” in the form of kernel code that can be executed and tested directly.
- The **TLA+** formalism has been successfully applied to discover bugs in the Linux kernel. Examples:
  - Confirmed a bug w.r.t. the correctness of memory management locking during a context switch
  - Bug w.r.t. fairness properties of the arm64 ticket spinlock implementation.

Automata and Linux

- **LTTng** [tracing tool] used to compare Linux execution against simple automata models.
  - Matni, Dagenais (2009)
- **SABRINE:** An approach using tracing and automata for *state-aware robustness testing* of OSes.
  - Trace are transformed into automata to group function into a state.
  - Cotroneo, Leo, Fucci, Natella (2013)
- **TIMEOUT** extends **SABRINE** with timing information for RTOS
  - Shahpasand, Sedaghat, Paydar (2016)

PREEMPT_RT Model

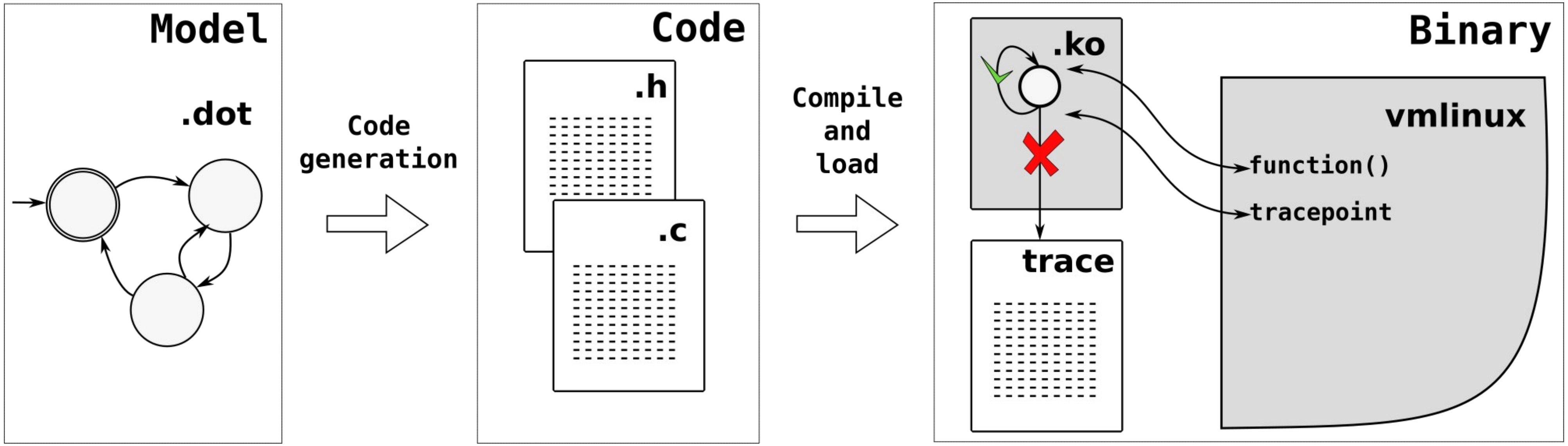
- **PREEMPT_RT Model** is an automata model that describe the interaction of the synchronization mechanisms and scheduling for threads, IRQs and NMIs.
  - Aiming to formally describe the dynamics of Real-time Linux.
  - de Oliveira, D.B., Cucinotta, T., de Oliveira, R.S.: **Untangling the Intricacies of Thread Synchronization in the PREEMPT RT Linux Kernel**. In: Proceedings of the IEEE 22nd International Symposium on Real-Time Distributed Computing (ISORC). Valencia, Spain (May 2019)
  - > 9k states and & > 23k transitions
- During the development, we found 4 bugs in kernel
  - 3 of them that could not be detected by any other tool

PREEMPT_RT Model

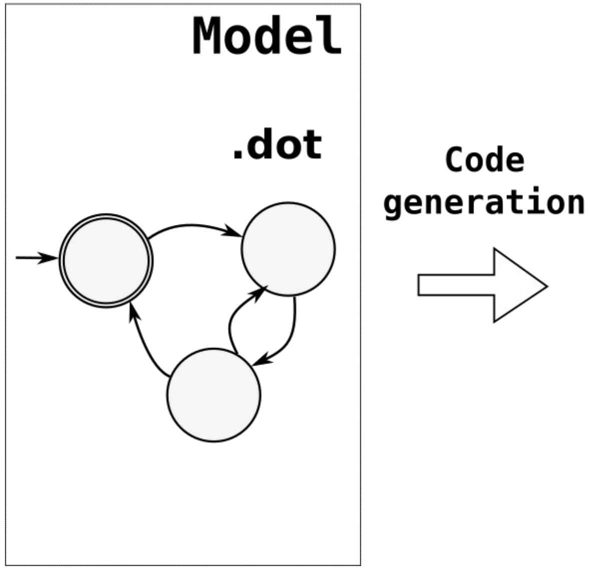
- **Linux kernel community** found value in the model for discovering bugs
  - **Automata seems to be a good abstraction** because of **tracing**
- The limitation of previous work:
  - The verification was done in user-space
  - Required the transfer of a considerable amount of data from kernel to user-space
    - 30 seconds of trace generates 2.5 GB of data/CPU!
    - No in-kernel actions could be taken in the case of an unexpected event
      - e.g., stacktrace, create a crash dump...

Efficient automata verification for the Linux Kernel

Proposed approach



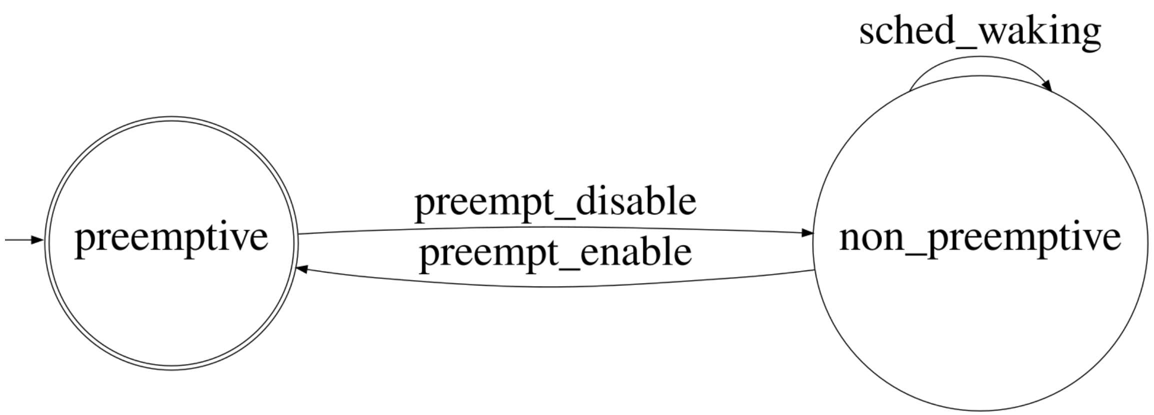
1) Code generation



- 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:

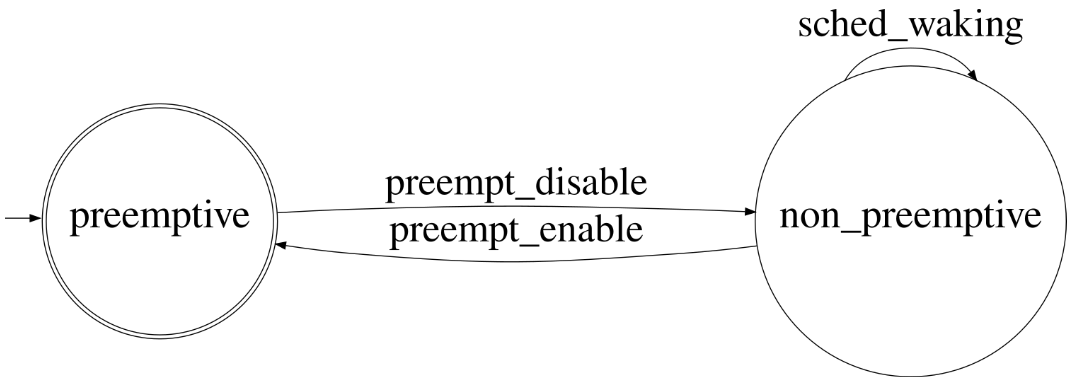
```
[bristot@t460s dot2c]$ ./dot2c wakeup_in_preemptive.dot
.....
```

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];
};
```



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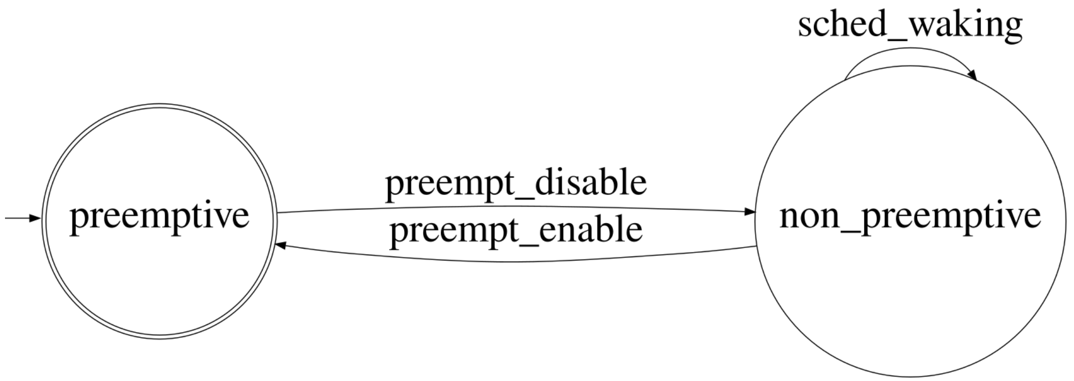
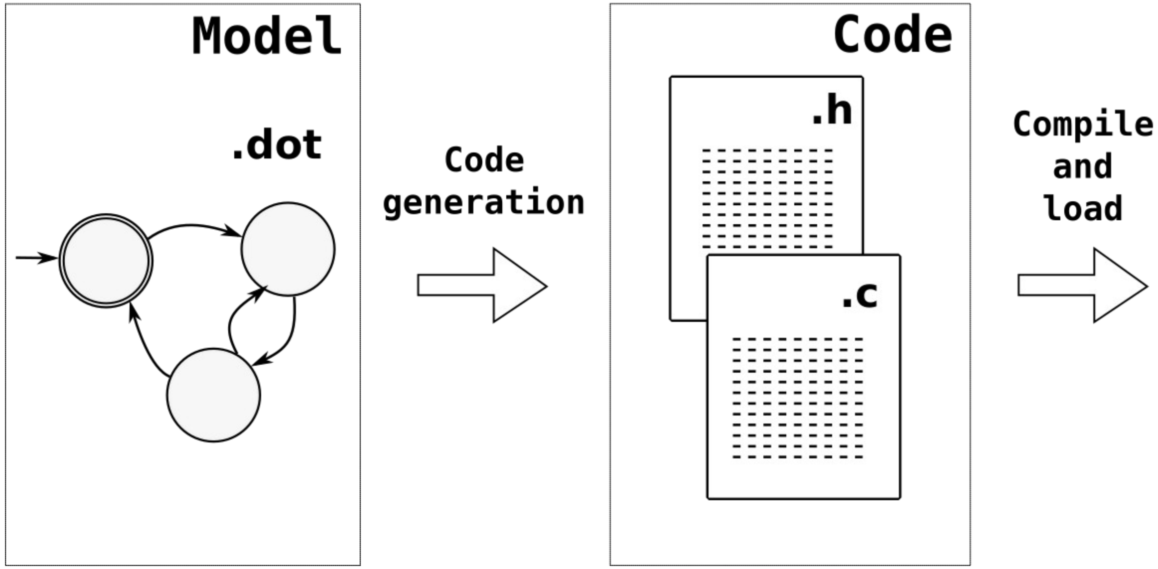
Automaton in C

```
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 }
};
```



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 != NULL) {
                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;
}
```

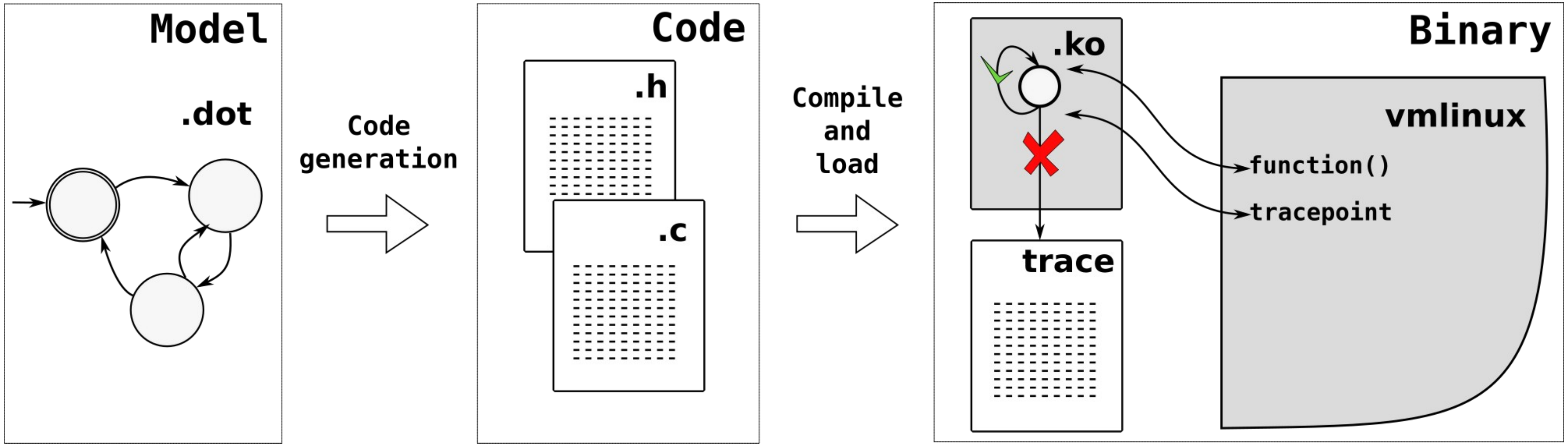
Processing one event

```
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)
{
        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;
}
```

All operations are O(1)!

Only one variable to keep the state!

3) Verification



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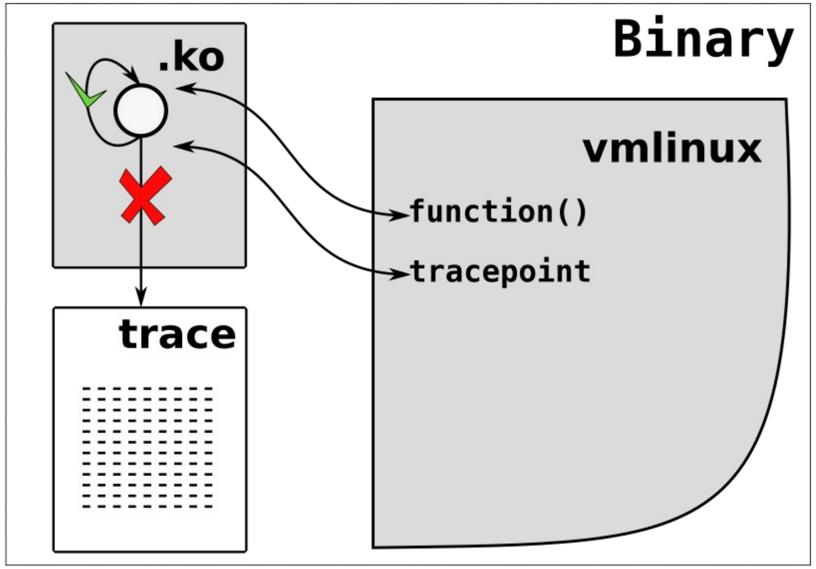
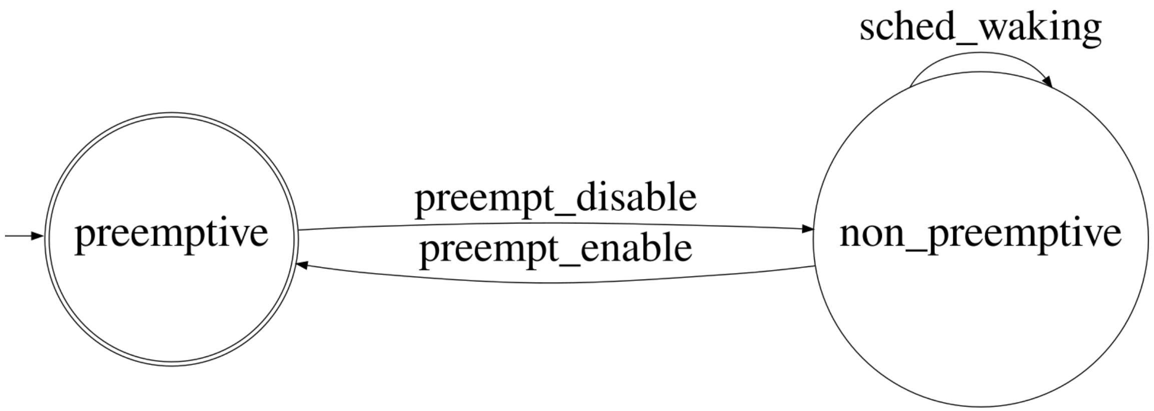
Verification

- 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

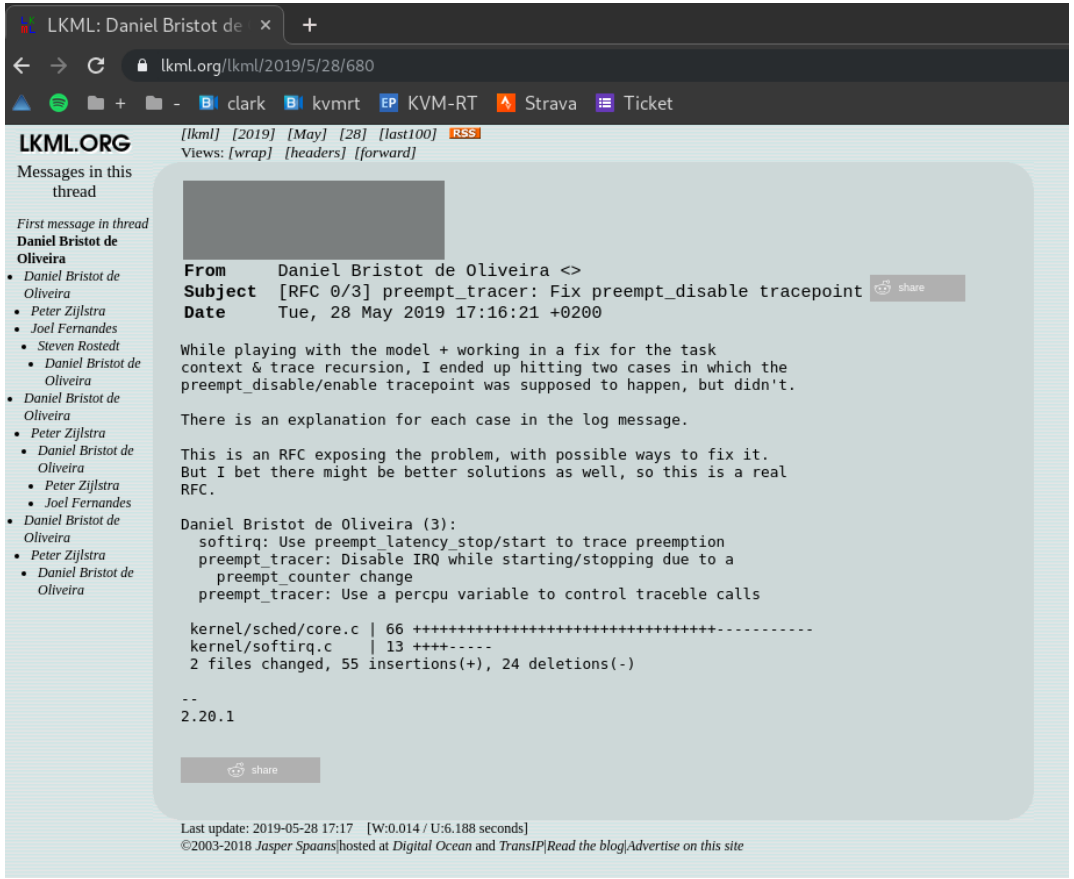
```
bash-1157  [003] ....2..   191.199172: process_event: non_preemptive -> preempt_enable = preemptive safe!
bash-1157  [003] dN..5..   191.199182: process_event: event sched_waking not expected in the state preemptive
bash-1157  [003] dN..5..   191.199186: <stack trace>
=> process_event
=> __handle_event
=> 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
```



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>



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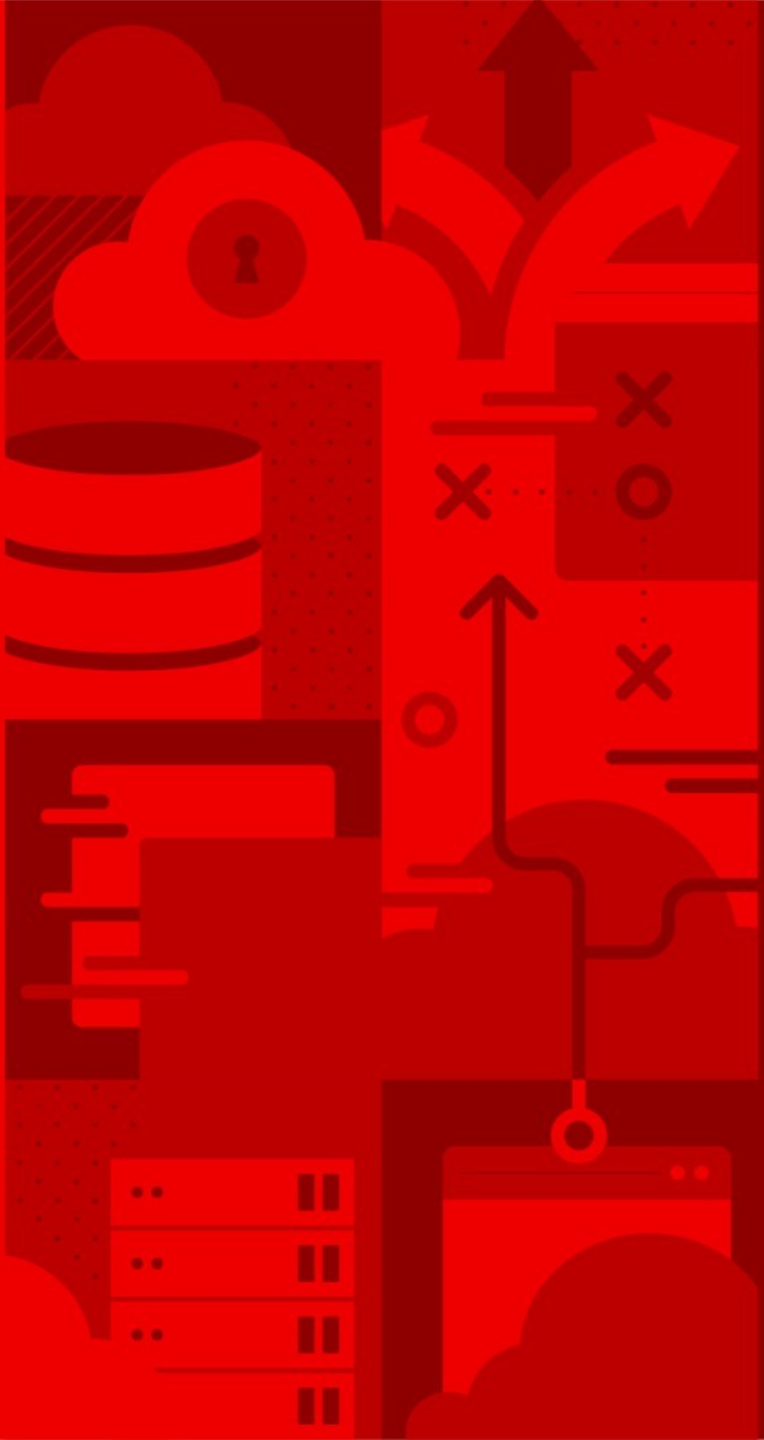
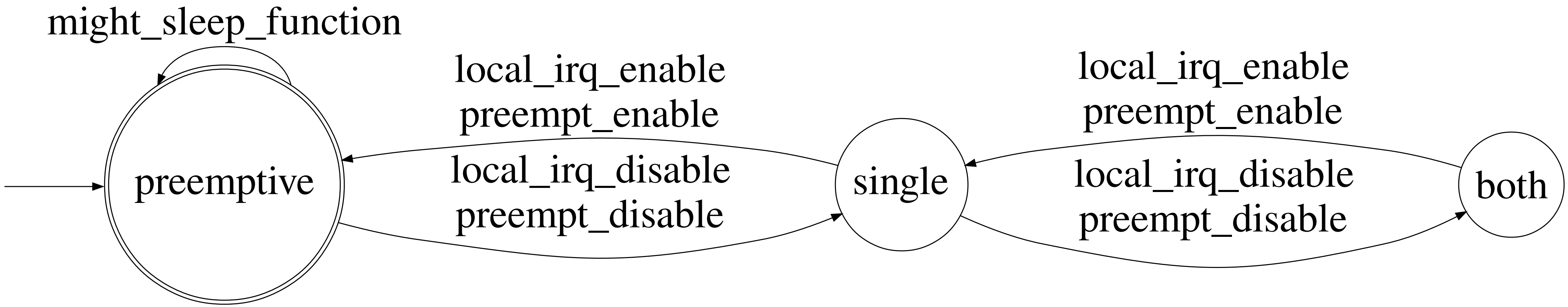


Performance evaluation

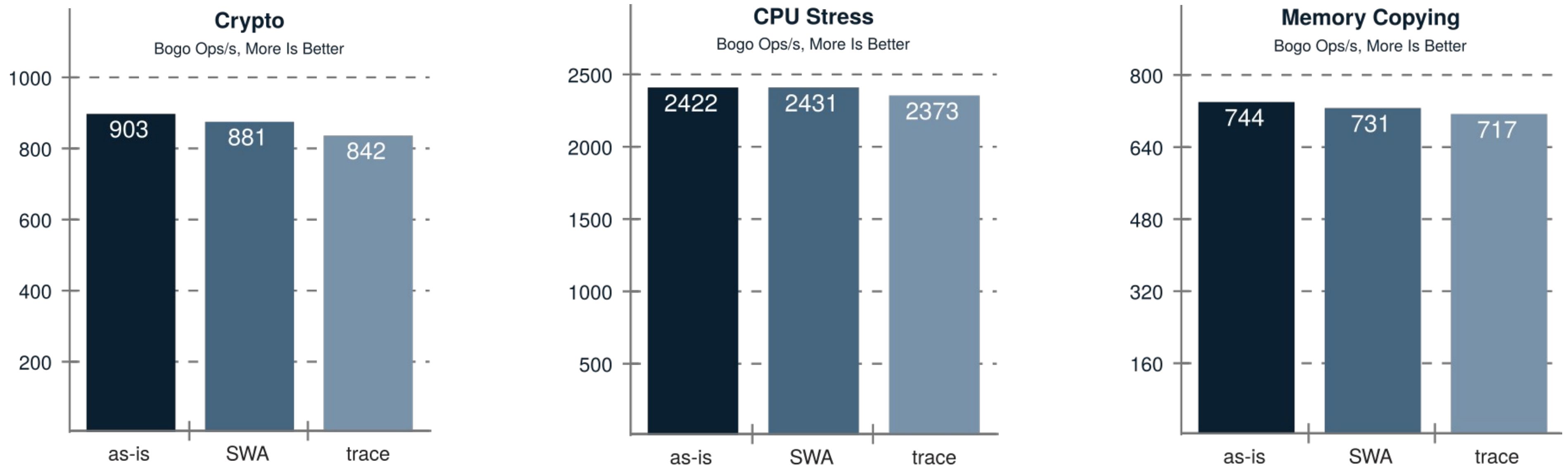
Efficiency in practice: a benchmark

- Two benchmarks
  - Throughput: Using the Phoronix Test Suite
  - (highest prio thread wake-up) 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.

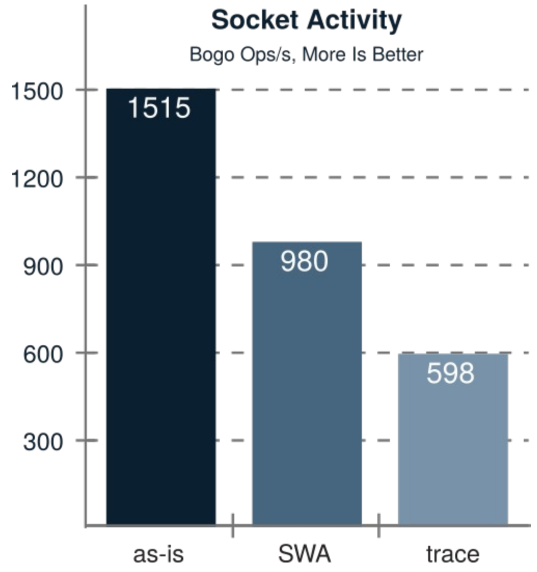
Throughput: SWA model

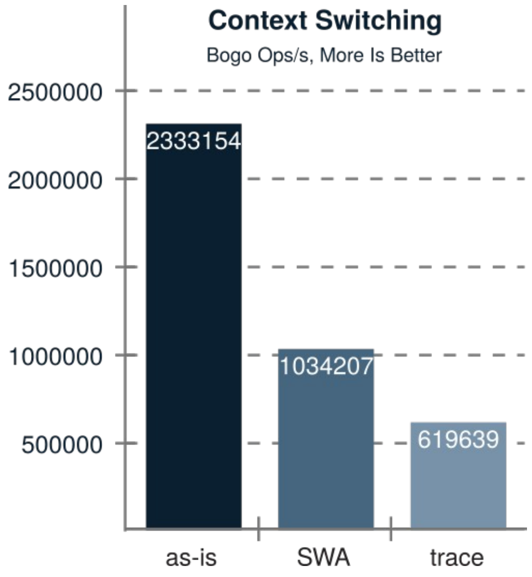


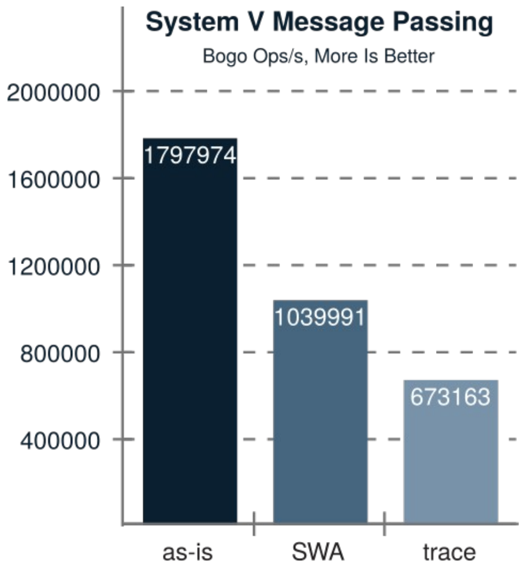
Benchmark: Thoughput – Low kernel activation



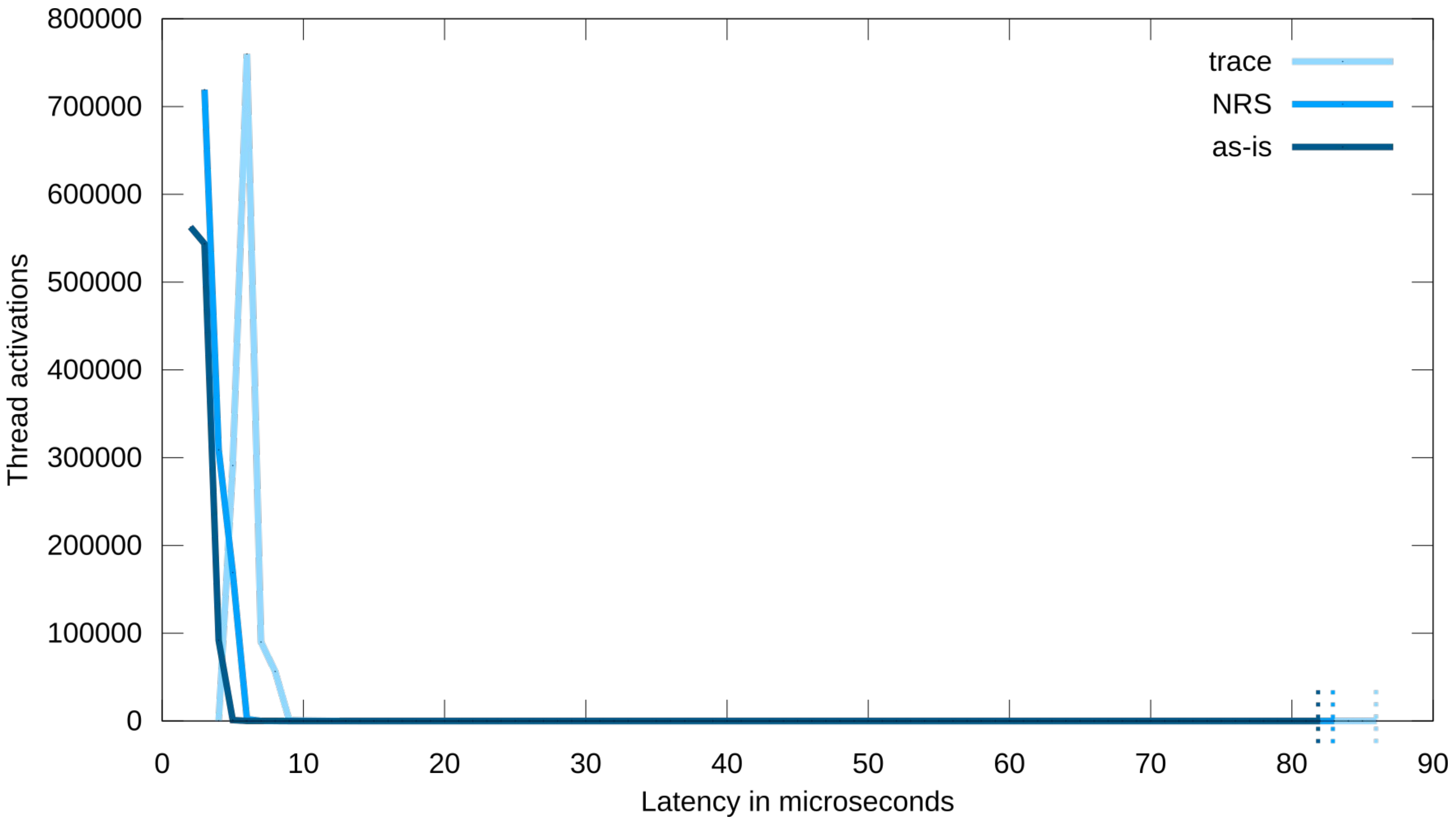
Benchmark: Thoughput – High kernel activation







Benchmark: Cyclictest latency



What it means?

- Trace is enable in production systems
- And is broadly used!
  - Hence, the verification can be done in production
  - This is useful mainly for debugging problems
    - Model the expected behavior
    - Wait for an unexpected event to happen

Future work

Future work

- Extend the work for parametric and/or timed automata
- Integrate the PREEMPT_RT model and this approach
- Create a better interface
  - Module is ok, but it can be better
    - Either integrated with ftrace or perf + eBPF
    - Having some models ready to be used, like trace!
- Creation of new models for the kernel
  - Recent update: we will try to model RCU

Thank you!
Questions?

This work is made in collaboration with:

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

Universidade Federal de Santa Catarina (Florianópolis - Brazil)