# Runtime verification of real-time applications using trace data and model requirements

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# Introduction

- Low-overhead tracing is available
- But trace analysis requires users to have kernel knowledge
- So what about automating the analysis ?
  - CAE suggested to verify applications' execution using specifications
  - Ericsson is working towards programming at model level
  - **Why couldn't we do both?**
- $\Rightarrow$ model-based constraints

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# Model representation

## What do we need?

- A way to follow the workflow of the application
  - $\Rightarrow$ tracepoints (or more precisely the events generated)
- A way to define the “zones” to check
- A way to define constraints

# Model representation

## What would our models look like?

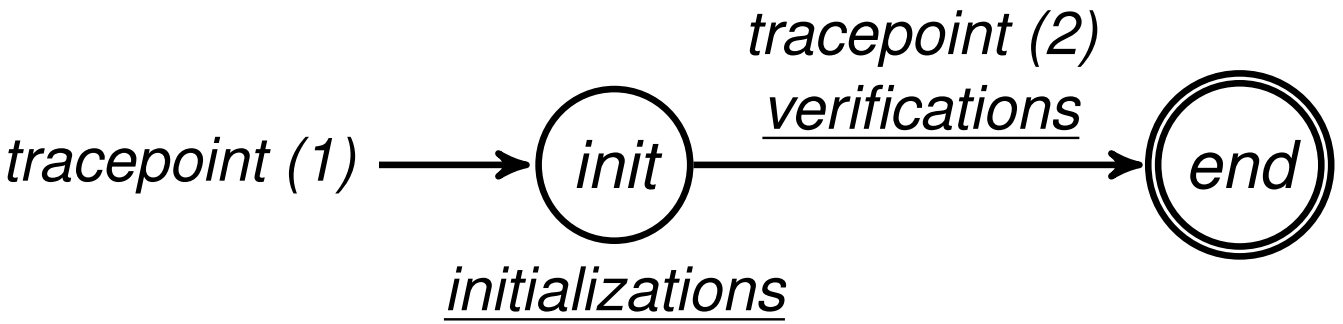



Figure: State machine representation that can be used to check metrics using traces

# Model representation

## What would our models look like?

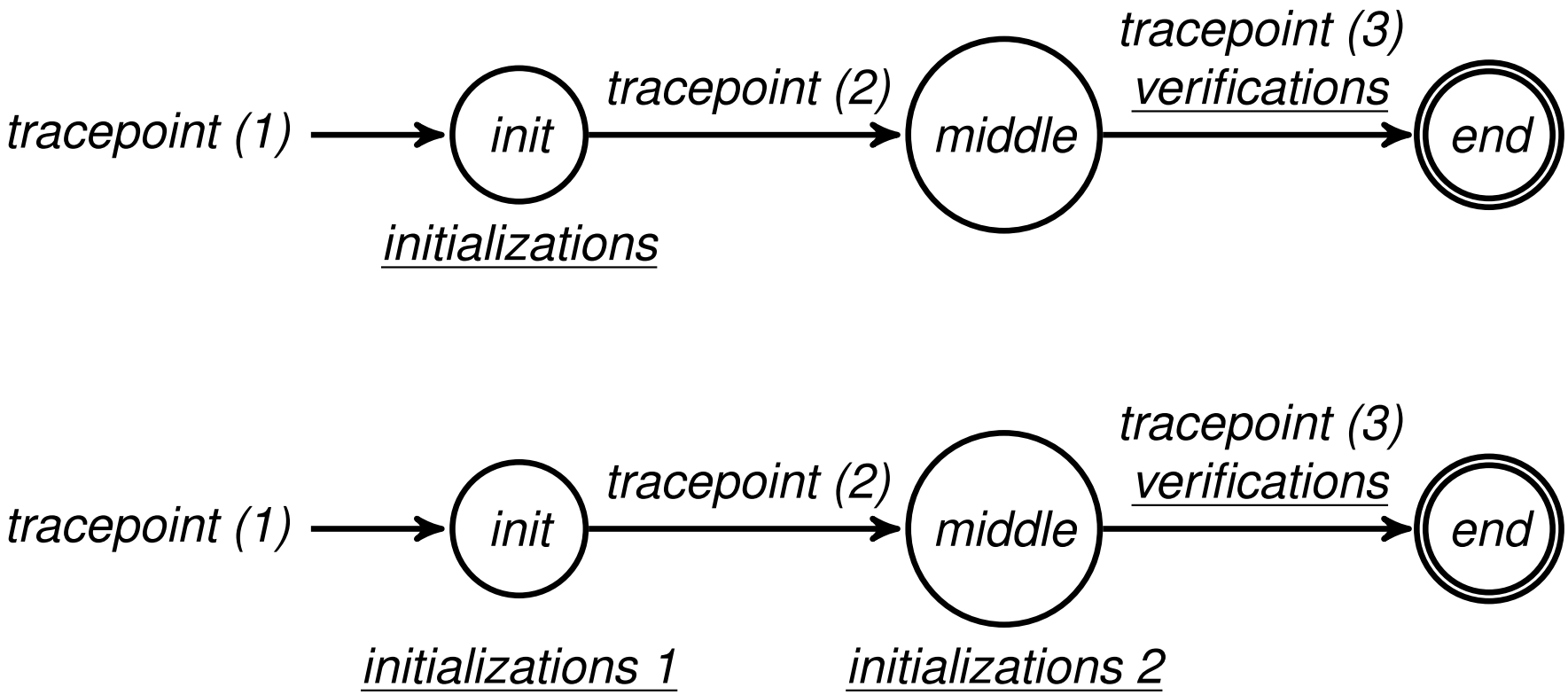



Figure: State machine representations with late verification of constraints and a transitional state

# Model representation

## What would our models look like?

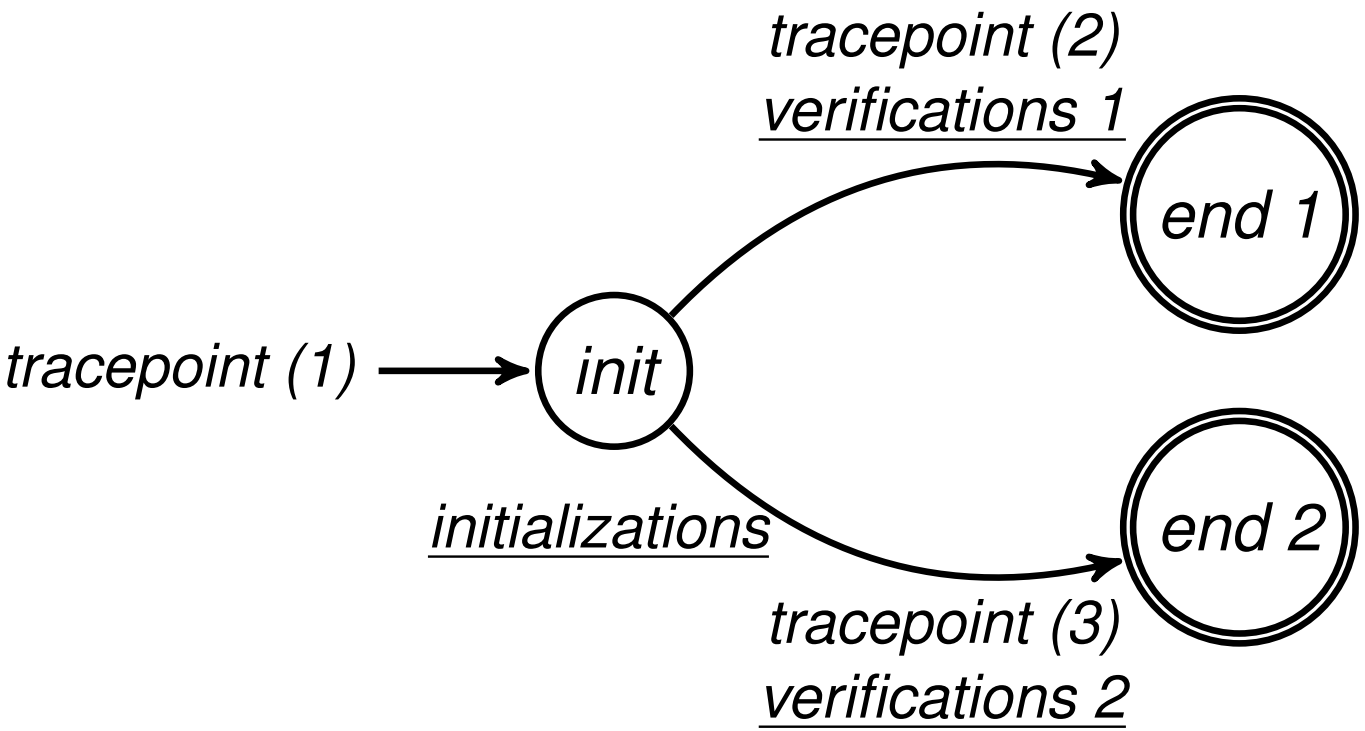



Figure: State machine representation with multiple next states for state “init”

# Model representation

## What would our models look like?

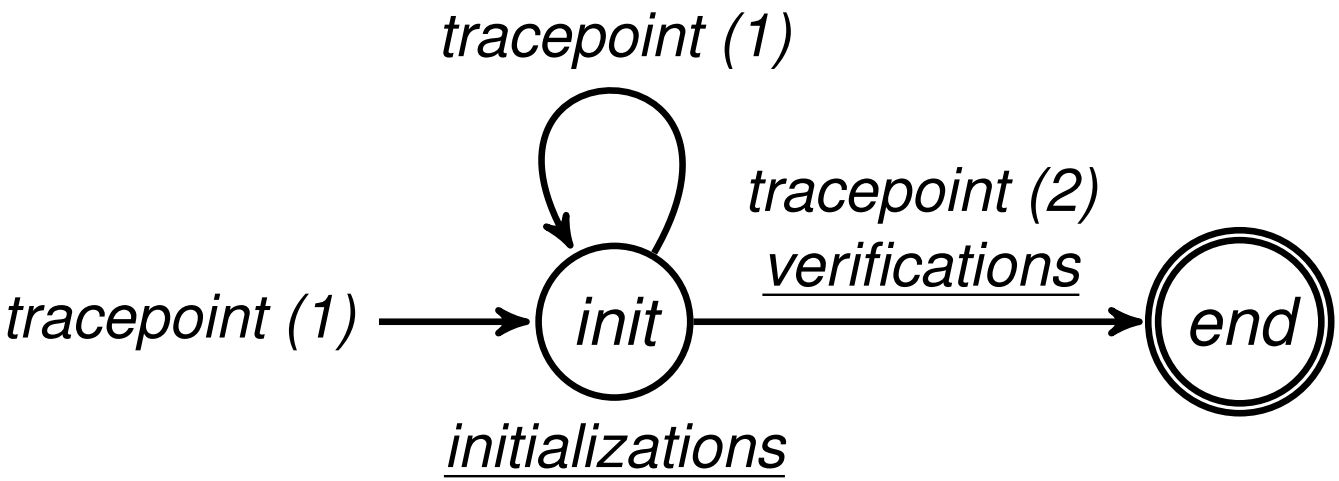
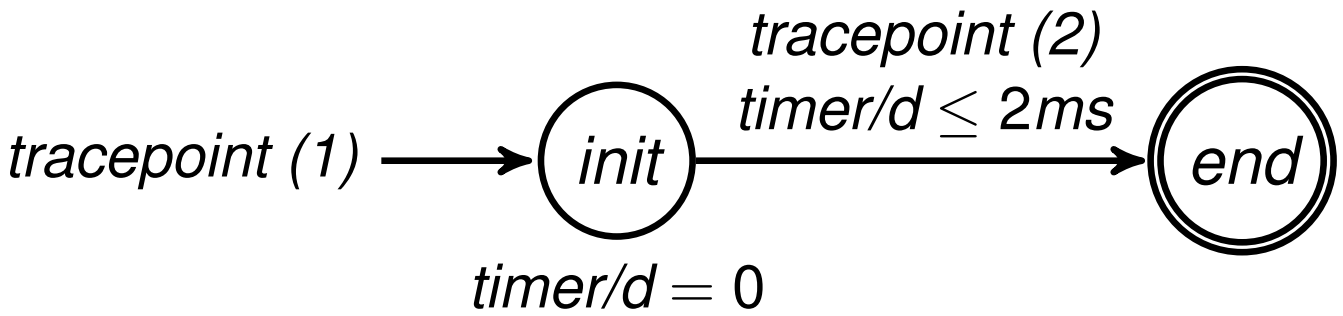



Figure: State machine representation using a loop to go over the initializations when reading an event generated by tracepoint (1)

# Sample constraints

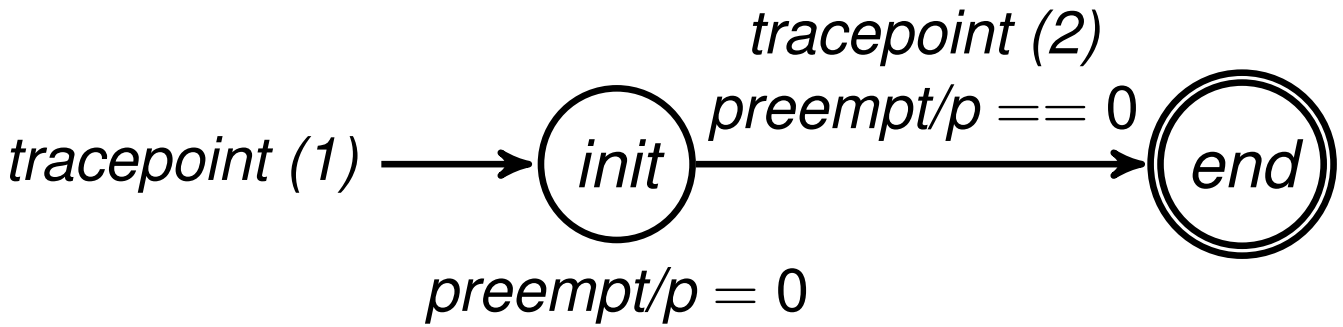
## Deadline constraint




- tracepoints *(1)* and *(2)* generate timestamped events
- timer/d $= 0$ saves the timestamp of the event from *(1)*
- timer/d $\leq 2ms$ verifies that the timestamp of the event from *(2)* is at most 2 ms after the one from *(1)*
- Needs only userspace traces

# Sample constraints

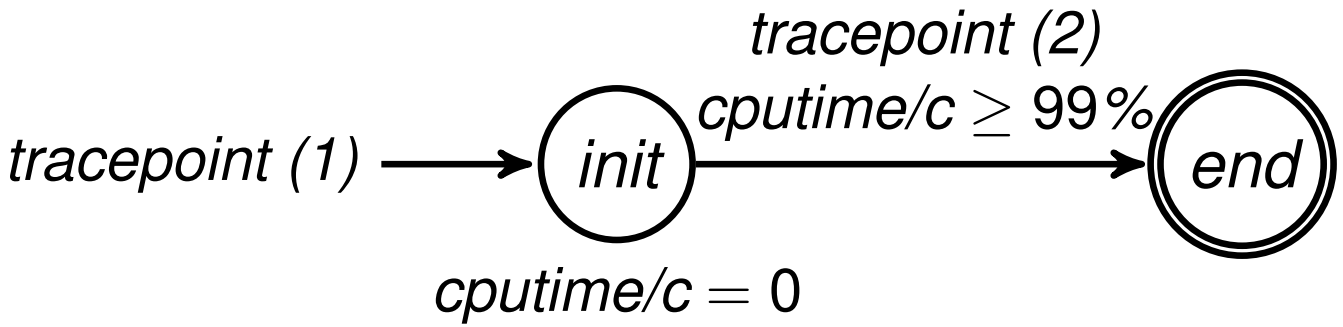
## Preemption constraint




- preempt/p = 0 initializes the counter to 0 at *(1)*
- preempt/p == 0 verifies that the counter is still 0 at *(2)* (i.e. counts the number of `sched_switch` during the period)
- Needs kernel and userspace traces
- Same idea: system calls constraint

# Sample constraints

## CPU usage constraint




- cputime/c $= 0$ sets the period start at *(1)*
- cputime/c $\geq$ 99% verifies that between *(1)* and *(2)* our process used at least 99 % of the CPU time
- Needs kernel and userspace traces
- Same idea: status constraint (wait-for-cpu, wait-blocked)

# Case studies

**. . . or how our approach could be used to detect some common problems**

1. Occasional missing of deadlines
2. Priority inversion
3. Unefficient synchronization method
4. Wait-blocked processes on multiprocessor activity
5. Wait-blocked processes while using external resources

# Case studies

## (1) Occasional missing of deadlines

### Problem

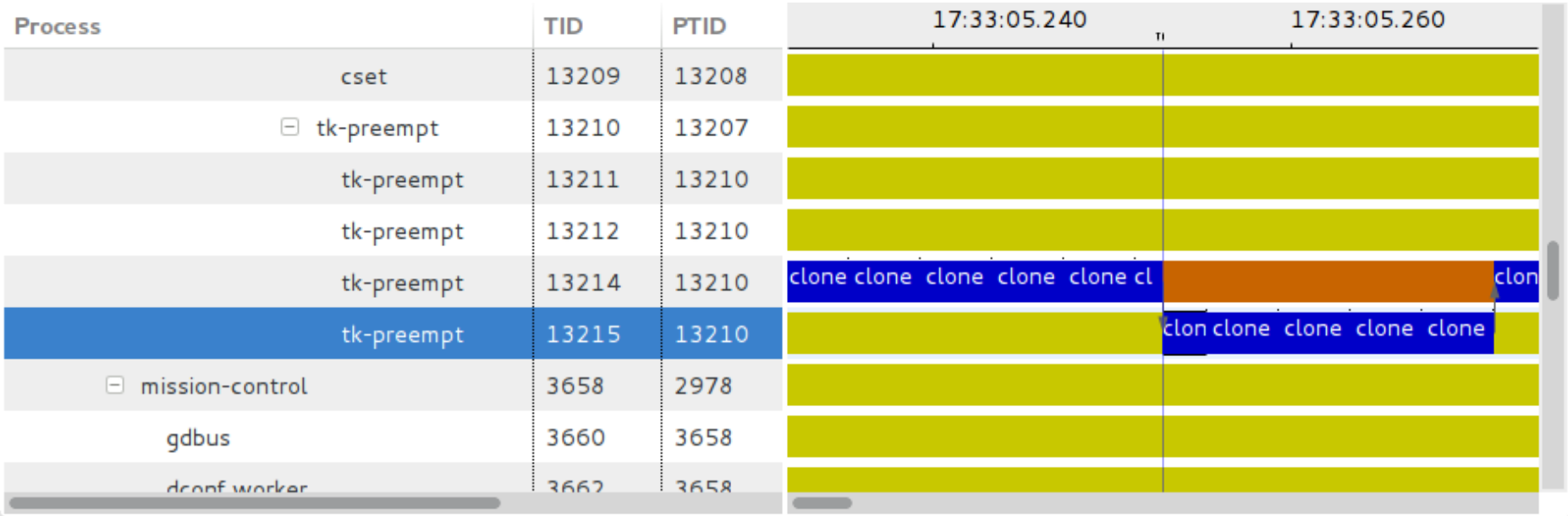
In a task that appears a lot of times, some deadlines are missed occasionnaly.

### Analysis

What happened on the kernel side when the deadlines were missed ?

# Case studies

## (1) Occasional missing of deadlines




ust/uid/0/64-bit | kernel

```
[17:33:05.252828753] (+0.000000748) computer
    sched_switch: { cpu_id = 2 }, { vtid = 13214, vpid =
    13210 }, { prev_comm = "tk-preempt", prev_tid =
    13214, prev_prio = -2, prev_state = 0, next_comm = "
    tk-preempt", next_tid = 13215, next_prio = -21 }
```

hrtimer=18446612150016859360, now=8091604000280, function=18446744071579722464, context._vtid=13215, contex

# Case studies

## (1) Occasional missing of deadlines

### Problem

In a task that appears a lot of times, some deadlines are missed occasionnaly.

### Analysis

What happened on the kernel side when the deadlines were missed ?

### Constraints that would have helped in our example

Deadline ; Preemption ; CPU usage

# Case studies

## (2) Priority inversion

### Problem

A high priority process still ends up being preempted by a lower priority process.

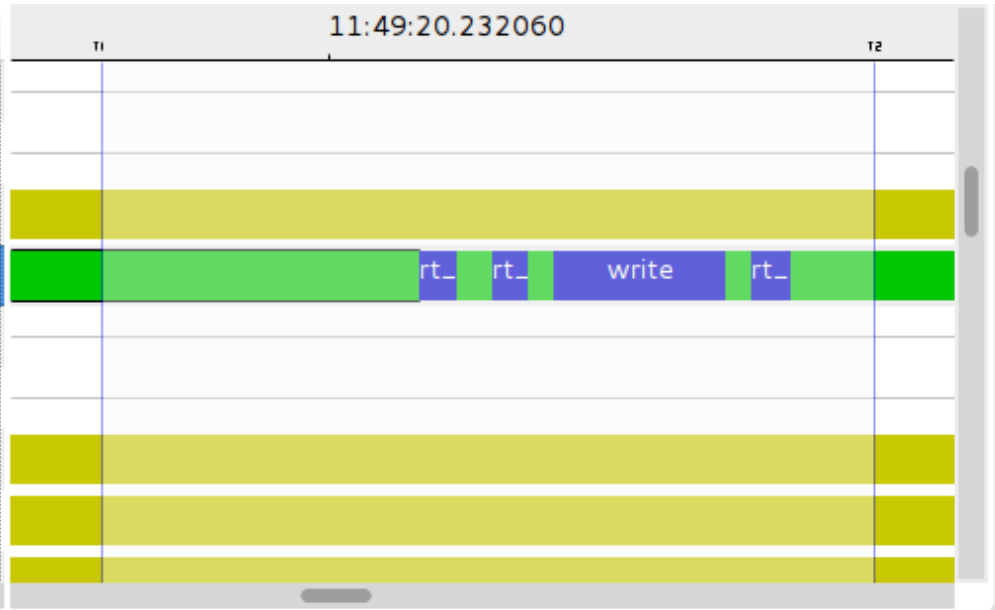
### Analysis

What happened that lead to that preemption?

# Case studies

## (2) Priority inversion

| | TID | PTID | Birth time |
|---|---|---|---|
| sudo | 6785 | 6736 | 11:49:04.711563346 |
| sh | 6786 | 6785 | 11:49:04.720466460 |
| sudo | 6787 | 6736 | 11:49:04.755070270 |
| npt | 6788 | 6787 | 11:49:04.763480843 |
| sudo | 6801 | 6736 | 11:49:51.725587947 |
| lttng | 6802 | 6801 | 11:49:51.857443514 |
| | 2857 | 1 | 11:49:04.688760858 |
| | 2874 | 1 | 11:49:04.688761987 |




kernel LTTng | kernel CAE | LTTng

```
hrtimer_cancel, hrtimer_expire_entry, softirq_raise,
rcu_utilization, softirq_raise, rcu_utilization,
hrtimer_expire_exit, hrtimer_start, sys_rt_sigpending,
exit_syscall, sys_rt_sigprocmask, exit_syscall,
sys_write, sched_wakeup, exit_syscall,
sys_rt_sigprocmask, exit_syscall
```

# Case studies

## (2) Priority inversion

### Problem

A high priority process still ends up being preempted by a lower priority process.

### Analysis

What happened that lead to that preemption?

### Constraints that would have helped in our example

CPU usage ; Preemption ; System calls

# Case studies

## (3) Unefficient synchronization method

### Problem

Some programs use `sleep` as a synchronization method.

### Analysis

- How much time a process has spent as wait-blocked? What was he waiting for?
- Analyze of `apt` using the critical path
- Analyze of `MongoDB` using the call stack and critical path

# Case studies

## (3) Unefficient synchronization method

### Problem

Some programs use `sleep` as a synchronization method.

### Analysis

- How much time a process has spent as wait-blocked? What was he waiting for?
- Analyze of `apt` using the critical path
- Analyze of `MongoDB` using the call stack and critical path

### Constraints that would have helped in our example

Deadline (using mean delay of task, for `MongoDB` it could be around 1 s for instance)

# Case studies

## (4) Wait-blocked processes on multiprocessor activity

### Problem

Scalability inefficiency: more processors $\Rightarrow$ less performance

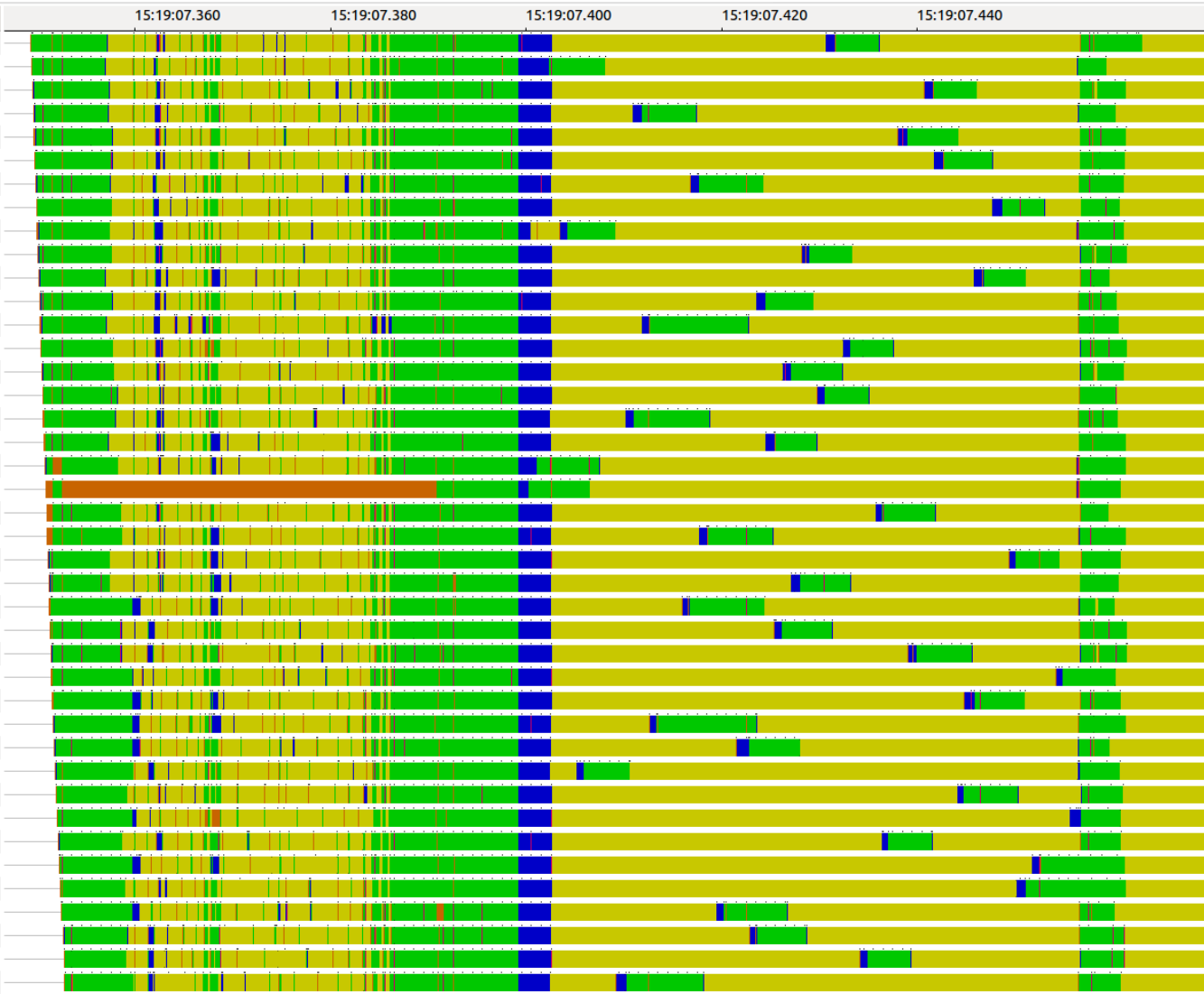
### Analysis

What happened between the last working scaling step and the first performance regression?

# Case studies

## (4) Wait-blocked processes on multiprocessor activity

| Process | TID | PTID | Birth time | Trace |
|---|---|---|---|---|
| io-test | 7659 | 7653 | 15:19:07.349273524 | io-test-large-chunk |
| io-test | 7660 | 7653 | 15:19:07.349362116 | io-test-large-chunk |
| io-test | 7661 | 7653 | 15:19:07.349466784 | io-test-large-chunk |
| io-test | 7662 | 7653 | 15:19:07.349567738 | io-test-large-chunk |
| io-test | 7663 | 7653 | 15:19:07.349653359 | io-test-large-chunk |
| io-test | 7664 | 7653 | 15:19:07.349730222 | io-test-large-chunk |
| io-test | 7665 | 7653 | 15:19:07.349803949 | io-test-large-chunk |
| io-test | 7666 | 7653 | 15:19:07.349883533 | io-test-large-chunk |
| io-test | 7667 | 7653 | 15:19:07.349955517 | io-test-large-chunk |
| io-test | 7668 | 7653 | 15:19:07.350034725 | io-test-large-chunk |
| io-test | 7669 | 7653 | 15:19:07.350114954 | io-test-large-chunk |
| io-test | 7670 | 7653 | 15:19:07.350198220 | io-test-large-chunk |
| io-test | 7671 | 7653 | 15:19:07.350270267 | io-test-large-chunk |
| io-test | 7672 | 7653 | 15:19:07.350343310 | io-test-large-chunk |
| io-test | 7673 | 7653 | 15:19:07.350416502 | io-test-large-chunk |
| io-test | 7674 | 7653 | 15:19:07.350511038 | io-test-large-chunk |
| io-test | 7675 | 7653 | 15:19:07.350596689 | io-test-large-chunk |
| io-test | 7676 | 7653 | 15:19:07.350672078 | io-test-large-chunk |
| io-test | 7677 | 7653 | 15:19:07.350753453 | io-test-large-chunk |
| io-test | 7678 | 7653 | 15:19:07.350837615 | io-test-large-chunk |
| io-test | 7679 | 7653 | 15:19:07.350911700 | io-test-large-chunk |
| io-test | 7680 | 7653 | 15:19:07.350986857 | io-test-large-chunk |
| io-test | 7681 | 7653 | 15:19:07.351058482 | io-test-large-chunk |
| io-test | 7682 | 7653 | 15:19:07.351130601 | io-test-large-chunk |
| io-test | 7683 | 7653 | 15:19:07.351204445 | io-test-large-chunk |
| io-test | 7684 | 7653 | 15:19:07.351278853 | io-test-large-chunk |
| io-test | 7685 | 7653 | 15:19:07.351348336 | io-test-large-chunk |
| io-test | 7686 | 7653 | 15:19:07.351418551 | io-test-large-chunk |
| io-test | 7687 | 7653 | 15:19:07.351527255 | io-test-large-chunk |
| io-test | 7688 | 7653 | 15:19:07.351617418 | io-test-large-chunk |
| io-test | 7689 | 7653 | 15:19:07.351720711 | io-test-large-chunk |
| io-test | 7690 | 7653 | 15:19:07.351805365 | io-test-large-chunk |
| io-test | 7691 | 7653 | 15:19:07.351882896 | io-test-large-chunk |
| io-test | 7692 | 7653 | 15:19:07.352032911 | io-test-large-chunk |
| io-test | 7693 | 7653 | 15:19:07.352123417 | io-test-large-chunk |
| io-test | 7694 | 7653 | 15:19:07.352213516 | io-test-large-chunk |
| io-test | 7695 | 7653 | 15:19:07.352303961 | io-test-large-chunk |
| io-test | 7696 | 7653 | 15:19:07.352391671 | io-test-large-chunk |
| io-test | 7697 | 7653 | 15:19:07.352637963 | io-test-large-chunk |
| io-test | 7698 | 7653 | 15:19:07.352722317 | io-test-large-chunk |
| io-test | 7699 | 7653 | 15:19:07.352781222 | io-test-large-chunk |



# Case studies

## (4) Wait-blocked processes on multiprocessor activity

### Problem

Scalability inefficiency: more processors $\Rightarrow$ less performance

### Analysis

What happened between the last working scaling step and the first performance regression?

### Constraints that would have helped in our example

CPU usage ; Process status (wait-blocked)

# Case studies

## (5) Wait-blocked processes while using external resources

### Problem

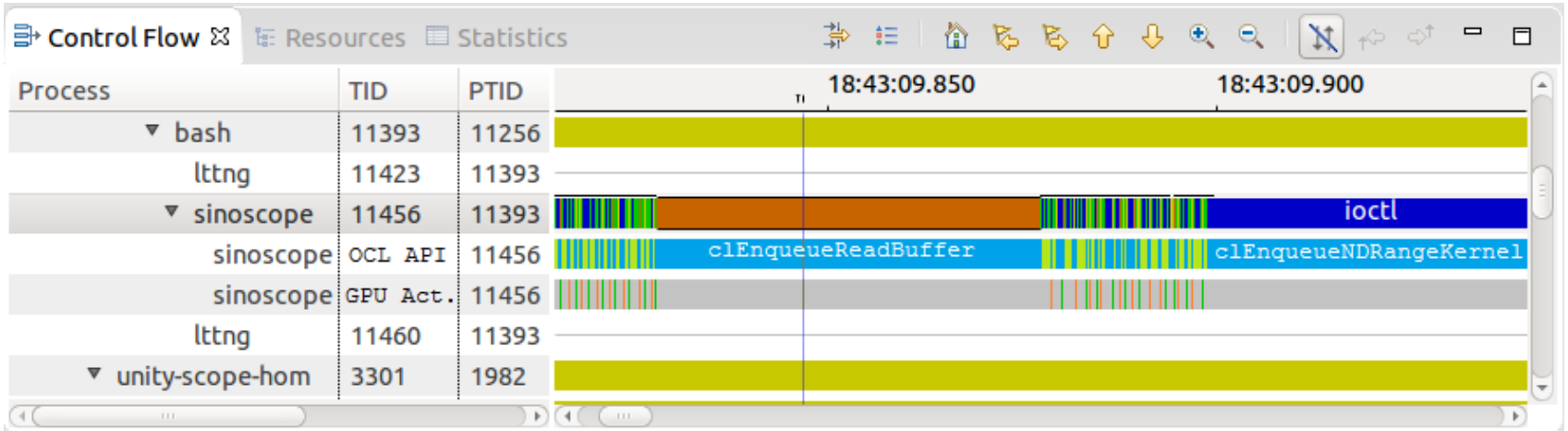
When using external resources such as GPU, bottlenecks can appear if the CPU-GPU work is not optimized

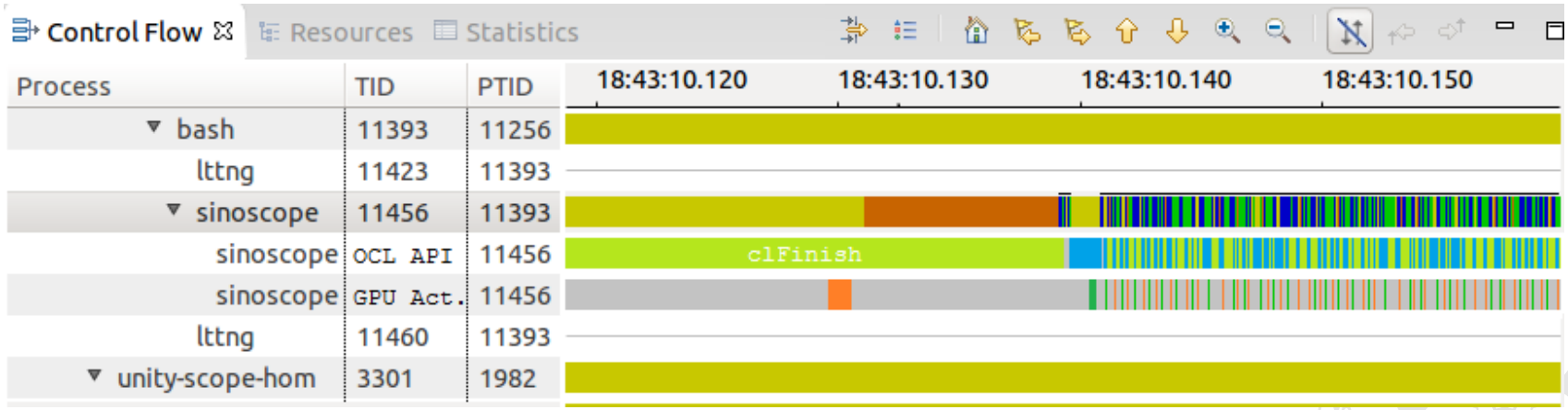
### Analysis

Was it caused by the CPU? By the GPU? What was the CPU process waiting for?

# Case studies

## (5) Wait-blocked processes while using external resources



# Case studies

## (5) Wait-blocked processes while using external resources

### Problem

When using external resources such as GPU, bottlenecks can appear if the CPU-GPU work is not optimized

### Analysis

Was it caused by the CPU? By the GPU? What was the CPU process waiting for?

### Constraints that would have helped in our example

CPU: preemption or Status (wait-blocked) $\Rightarrow$ always scheduled
GPU: Status (wait-blocked) if we know the GPU task duration

# Conclusion

- New approach using constraints to automatically detect problems using traces
- Overview of high performance cases where tracing was useful to identify an unexpected behavior
- Automatic identification of those behaviors using our model approach
- Range of problems we can detect is larger than what the literature provides thanks to kernel tracing
- Future work:
  - Identify the origins of the detected problems
  - Propose simple solutions for those problems (e.g. higher priority for a preempted process)

# Thank you.
# Any question?

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Slides:
www.dorsal.polymtl.ca/~rbeamonte/dorsal-pm-may2015.pdf