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

Progress Report Meeting
May 5, 2016

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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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Variables

Counters variables incremented each time *something* happens (i.e. number of system calls)

Timers variables following the duration of *something* (i.e. cpu usage)

State system free variables based on userspace events (i.e. deadline)

Algorithms

Two approaches

- When the constraint is absolute *(counter* $==0$, *timer* $==100\%, \ldots)$
  - Every occurrence is a problem: classify by level of responsibility
- When the constraint is relative
  - How can you find the problem ?
  - $\Rightarrow$ **Compare valid and invalid instances**

Algorithms

Data extraction: what should we compare?

Counters the events that increment the counter (i.e. `syscall_entry_*` for system calls)

Timers the occurrences and durations of periods incrementing the timer (i.e. `sched_switch` to unschedule then to schedule back for cpu usage)

State system free kind of everything that happens in the period that influences the variable (i.e. the state of the process for a dealine)

Algorithms

Weighting of valid instances

The **weight** is computed by:

$$W_i = W_{r\,i} - P$$

With the uncertainty penalty $P = F_C \times \left(1 - \frac{1}{N_{valid}}\right)$ $(F_C = 0.1)$

And the relative weight $W_{r\,i}$:

$$W_{r\,i} = \frac{O_i}{\sum_{d_j \le d_i} O_j} \times \frac{d_i}{\max(1, s)} + \frac{s - d_i}{\max(1, s)}$$

With:

- O_i the number of occurrences of the valid list i
- d_i the distance between this list and the invalid one
- $\sum_{d_j \le d_i} O_j$ the sum of O_j for all list j with $d_j <= d_i$
- s the size (or number of elements) of the invalid list

Case studies

Examples of results: Too low priority (jackd)

- Run a real-time application (`JACK2`, the audio server) with a low real-time priority (-1), and pinned on a given CPU (2)
- Force its preemption by running another application (cpuburn) on the same CPU, with a higher priority

```
$ taskset -c 0 jackd -P 1 -v -d alsa -H
...
creating alsa driver ... hw:0|hw:0|1024|2|48000|0|0|
    hwmon|swmeter|-|32bit
configuring for 48000Hz, period = 1024 frames (21.3 ms),
     buffer = 2 periods
...
Jack: alsa_pcm: xrun of at least 353.963 msecs
```

Case studies: Too low priority (jackd)

Invalid interval set

```
IntervalSet(1): [
    [BLOCKED on poll, 3, [4.1705323E7, 4.1705323E7]]
    [RUNNING, 14, [238189.0, 238189.0]]
    [SYSCALL futex, 1, [10094.0, 10094.0]]
    [Interrupted by IRQ29 (snd_hda_intel), 1, [977.0, 977.0]]
    [WAKING, 3, [5.85536417E8, 5.85536417E8]]
    [SYSCALL poll, 6, [58995.0, 58995.0]]
    [SYSCALL ioctl, 5, [103256.0, 103256.0]]
    [SYSCALL write, 5, [31727.0, 31727.0]]
]
```

Case studies: Too low priority (jackd)

Valid interval sets weighting against invalid one

Valid list	Distance	Occurrences	Weight
IntervalSet(105): [[BLOCKED on poll, 2, [2.0703525E7, 2.2803038E7]] [RUNNING, 3, [31941.0, 111629.0]] [WAKING, 2, [10907.0, 85443.0]] [SYSCALL poll, 4, [34946.0, 90288.0]]]	30	105	93.33%
IntervalSet(2): [[BLOCKED on poll, 2, [2.0767886E7, 2.17529E7]] [RUNNING, 3, [61252.0, 87261.0]] [WAKING, 2, [15856.0, 23237.0]] [SYSCALL poll, 5, [43815.0, 76711.0]] [Interrupted by HRTIMER, 1, [5848.0, 15496.0]]]	31	2	13.28%
IntervalSet(4): [[BLOCKED on poll, 2, [2.0757138E7, 2.1794678E7]] [RUNNING, 4, [46599.0, 115511.0]] [WAKING, 2, [13054.0, 24173.0]] [SYSCALL poll, 4, [32867.0, 61412.0]] [Interrupted by HRTIMER, 1, [7908.0, 12598.0]]]	33	4	9.62%

Case studies: Too low priority (jackd)

Computed interval set difference *(using only weights >= 50%)*

```
Diff: [
    [RUNNING, 11, [126560.0, 206248.0]]
    [BLOCKED on poll, 1, [1.8902285E7, 2.1001798E7]]
    [WAKING, 1, [5.85450974E8, 5.8552551E8]]
    [SYSCALL futex, 1, [10094.0, 10094.0]]
    [SYSCALL ioctl, 5, [103256.0, 103256.0]]
    [SYSCALL poll, 2, [0.0, 24049.0]]
    [SYSCALL write, 5, [31727.0, 31727.0]]
    [Interrupted by IRQ29 (snd_hda_intel), 1, [977.0, 977.0]]
]
```

Case studies: Too low priority (jackd)

Computed responsibility (state analysis)

State	Responsibility for added time
WAKING	96.65%
BLOCKED on poll	3.29%
RUNNING	0.03%
SYSCALL ioctl	0.02%
SYSCALL write	0.01%
SYSCALL poll	0.00%
SYSCALL futex	0.00%
Interrupted by IRQ29 (snd_hda_intel)	0.00%

Minimum responsibility for a case to be considered: 64.83%

Case studies: Too low priority (jackd)

Critical path analysis triggered by the state analysis

Critical path state	Responsibility for added time
jackd PREEMPTED	96.51%
swapper/0 RUNNING	1.88%
swapper/0 PREEMPTED	1.55%
jackd RUNNING	0.05%
irq/29-snd_hda_ PREEMPTED	0.01%
irq/29-snd_hda_ RUNNING	0.00%

Minimum responsibility for a case to be considered: 60.79%

Case studies: Too low priority (jackd)

CPUTop analysis triggered by the critical path analysis

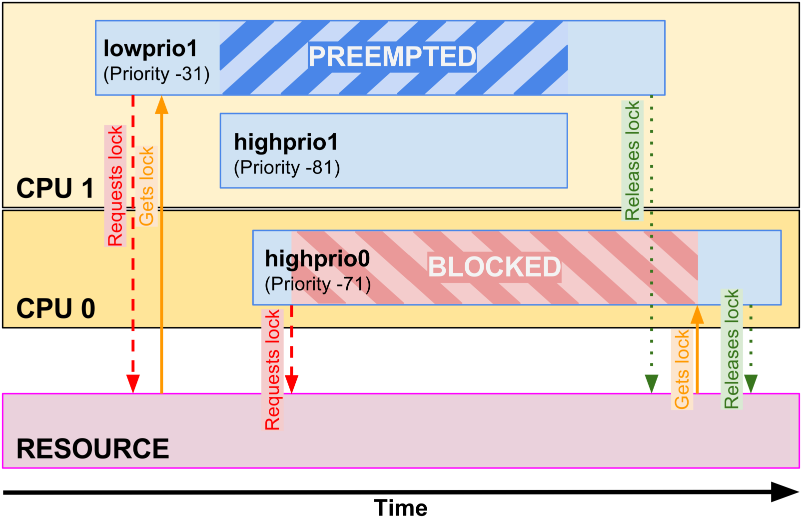
```
Analyzed CPUs: 0
Analyzed timerange: [11:54:37.711 896 155, 11:54:38.319 519 477]
```

Per-TID Usage	Process	Migrations	Priorities
96.34%	cpuburn (11371)	0	[-61]
0.29%	bash (11375)	1	[20]
0.13%	bash (11376)	2	[20]
0.11%	bash (11377)	0	[20]
0.10%	/usr/bin/x-term (3154)	2	[]

```
Priorities of the PREEMPTED process during that interval: -2
```

Case studies

Examples of results: In-kernel wake lock priority inversion



Case studies: In-kernel wake lock priority inversion

Computed responsibility (state analysis)

State	Responsibility for added time
BLOCKED on open	100.00%
RUNNING	0.00%
SYSCALL open	0.00%
SYSCALL gettid	0.00%

```
Minimum responsibility for a case to be considered: 56.70%
```

Case studies: In-kernel wake lock priority inversion

Priority inversion analysis triggered by the state analysis

```
Duration of active 'sched_pi_setprio'...
... in valid instances (maximum): 170.909us
... in invalid instances (average): 329.534us

Active 92.81% more time in invalid instances than in valid instances.

Verdict: Very high probability of a priority inversion
```

Critical path analysis triggered by the state analysis

Critical path state	Responsibility for added time
lowprio1 PREEMPTED	100.00%

```
Minimum responsibility for a case to be considered: 100.00%
```

Case studies: In-kernel wake lock priority inversion

CPUTop analysis triggered by the critical path analysis

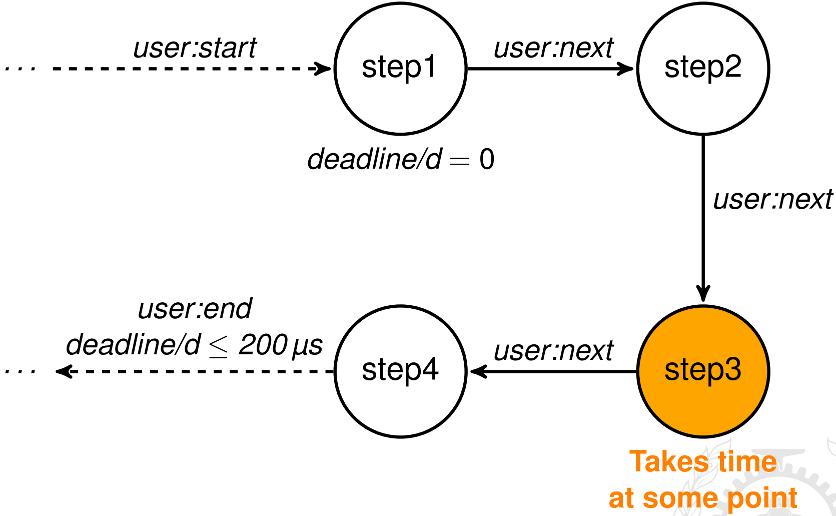
```
Analyzed CPUs: 1
Analyzed timerange: [21:40:35.867 825 012, 21:40:36.033 045 371]
```

Per-TID Usage	Process	Migrations	Priorities
99.18%	highprio1 (26408)	0	[-100, -81]
0.82%	lowprio1 (26407)	0	[-71]
0.00%	lttng-consumerd (26369)	0	[20]
0.00%	lttng-consumerd (26370)	0	[20]
0.00%	Cache2 I/O (3011)	0	[20]

```
Priorities of the PREEMPTED process during that interval: -71
```

Case studies

Examples of results: Bad code



Case studies: Bad code

Computed responsibility (state analysis)

State	Responsibility for added time
RUNNING	99.89%
Interrupted by HRTIMER	0.04%
Interrupted by SOFTIRQ_TIMER	0.03%
Interrupted by SOFTIRQ_RCU	0.02%
SYSCALL write	0.02%
Interrupted by SOFTIRQ_SCHED	0.00%
SYSCALL gettid	0.00%

Minimum responsibility for a case to be considered: 64.94%

Case studies: Bad code

State machine state analysis triggered by the state analysis

Model state	Responsibility for added time
step3	99.92%
step1	0.05%
step4	0.03%
step2	0.01%

Case studies

Examples of results: Preempted waker

- Instrumentation of `cyclictest` to take a snapshot when a period goes over a threshold
- The application was then started on a machine, and ran for a considerable amount of time before saving the trace
- We didn't know what happened. We used our analysis approach on it.

Case studies: Preempted waker

Computed responsibility (state analysis)

State	Responsibility for added time
BLOCKED on rt_sigtimedwait	99.95%
RUNNING	0.03%
SYSCALL getcpu	0.01%
SYSCALL clock_gettime	0.01%

Minimum responsibility for a case to be considered: 56.68%

Case studies: Preempted waker

Critical path analysis triggered by the state analysis

Critical path state	Responsibility for added time
ktimersoftd/3 PREEMPTED	99.68%
ktimersoftd/3 RUNNING	0.24%
cyclictest PREEMPTED	0.08%

Minimum responsibility for a case to be considered: 52.77%

Case studies: Preempted waker

CPUTop analysis triggered by the critical path analysis

```
Analyzed CPUs: 3
Analyzed timerange: [15:55:53.528 529 561, 15:55:53.536 012 105]
```

Per-TID Usage	Process	Migrations	Priorities
99.73%	irq/154-hpd (162)	0	[-51]
0.26%	irq/25-54200000 (163)	0	[-51]
0.01%	ktimersoftd/3 (32)	0	[-2]
0.00%	irq/22-Tegra PC (160)	0	[-51]
0.00%	irq/388-eth0 (611)	0	[-51]

```
Priorities of the PREEMPTED process during that interval: -2
```

Case studies

Last case: Frequency scaling

- Context: trying to generate a case for our analysis
- More exactly... to break an application workflow
- But... the "should be valid" and "should be invalid" case were having similar durations
- These durations were between 6 ms to 12 ms for each instance
- After a few number of tries... We got it! We forgot to disable frequency scaling.
- ... We could have saved some time.

Frequency scaling analysis

CPU frequency for valid instances:

CPU Frequency	Percent of time
2661.00 MHz	83.09%
2660.00 MHz	11.85%
2527.00 MHz	5.06%

Average frequency: 2654.10 MHz

CPU frequency for invalid instances:

CPU Frequency	Percent of time
1596.00 MHz	39.77%
2527.00 MHz	24.97%
2661.00 MHz	18.36%
Unknown	8.55%
2660.00 MHz	8.36%

Average frequency: 2161.23 MHz

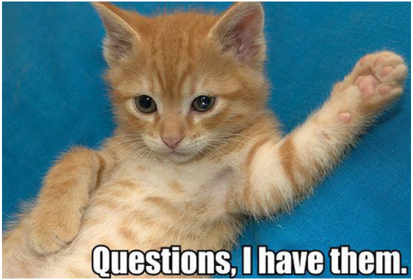
22.81% higher average frequency in valid than in invalid instances.

Verdict: Probability of a frequency scaling problem

Conclusion

- New approach using constraints to automatically detect problems using traces
- Algorithms to do an analysis of the constraints violations
- Presentation of the analysis results of multiple and common real-time problems
- Future work:
  - Write the paper that comes with that!
  - Track 3 of the Ph.D. $\Rightarrow$ from trace to model-based constraints

Thank you.
Any question?



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Slides:
`secretaire.dorsal.polymtl.ca/∼rbeamonte/dorsal-pm-may2016.pdf`