Open Source in Industry: Linux tracing and debugging

Technical Heidelberg OSADL Talks, September 30, 2020, Online Session 2a

Debug and trace interface of the Linux kernel
Function tracing
Event tracing
Latency tracing

What is „ftrace“?

Initially, “ftrace” was a function tracer, i.e. a log system that could be enabled to record every time a function was called and returned along with names of the calling and the called function and a time stamp.

Today, the term “ftrace” is history, a better word is „tracing“ or „kernel tracing“. It includes a variety of method that are used to understand kernel failures and help fixing them.

The important common functionality is a FIFO that is optimized for speed and combines all tracing messages into a single data stream.

How do we communicate with the tracing interface?

The virtual file system to access kernel tracing is the same as for all other debug subsystems of the kernel (usually automatically mounted):

```
# mount -t debugfs nodev /sys/kernel/debug
```

The interface to the tracing system is localized in the

```
/sys/kernel/debug/tracing
```

directory.

Main functionality of kernel tracing

1. “Classical” function tracer with dynamic function selection
2. Event tracer
3. Tracer of certain critical sections
4. Printk tracer
5. Hardware latency tracer

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Provides: Function name and timing
Advantage: Fast
Disadvantage: No arguments

Main functionality of kernel tracing

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Provides: Individually specified data
Advantage: Plenty of information
Disadvantages: Slow

Main functionality of kernel tracing

1. “Classical” function tracer with dynamic function selection
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5. Hardware latency tracer

Advantage over Syslog:
Much faster and independent
from user-space program

Data exchange with the tracers

```
ls /sys/kernel/debug/tracing

available_events            ksym_trace_filter   sysprof_sample_period
available_filter_functions  latency_hist        trace
available_tracers           options             trace_clock
buffer_size_kb              per_cpu             trace_marker
current_tracer              printk_formats      trace_options
dyn_ftrace_total_info       README              trace_pipe
events                      saved_cmdlines      tracing_cpumask
failures                    set_event           tracing_enabled
kprobe_events               set_ftrace_filter   tracing_max_latency
kprobe_profile              set_ftrace_notrace  tracing_on
ksym_profile                set_ftrace_pid      tracing_thresh
```

Data exchange with the tracers

This is the most important virtual file

```
ls /sys/kernel/debug/tracing

available_events            ksym_trace_filter    sysprof_sample_period
available_filter_functions  latency_hist         trace
available_tracers           options              trace_clock
buffer_size_kb              per_cpu              trace_marker
current_tracer              printk_formats       trace_options
dyn_ftrace_total_info       README               trace_pipe
events                      saved_cmdlines       tracing_cpumask
failures                    set_event            tracing_enabled
kprobe_events               set_ftrace_filter    tracing_max_latency
kprobe_profile              set_ftrace_notrace   tracing_on
ksym_profile                set_ftrace_pid       tracing_thresh
```

Read the tracing FIFO

```
cd /sys/kernel/debug/tracing
```

All CPUs:

```
cat trace >/tmp/trace.txt
```

A defined CPU only, e.g. core #0 :

```
cat per_cpu/cpu0/trace >/tmp/trace-cpu0.txt
```

Function tracer

Test whether function tracer is available:

```
# grep function available_tracers
hwlat blk mmiotrace function_graph wakeup_dl wakeup_rt wakeup function nop
```

Enable function tracer:

```
# echo function >current_tracer
```

Enables all functions the name of which begins with "sys_"

Enable tracer only for selected functions:

```
# echo <[*]function[*]> >set_ftrace_filter
```

For example: `echo sys_* >set_ftrace_filter`

Stop tracing:

```
# echo 0 >tracing_enabled
```

Function tracer example (nop=disabled)

```
# cat trace
# tracer: nop
#
# entries-in-buffer/entries-written: 0/0   #P:32
#
#                              _-----=> irqs-off
#                             / _----=> need-resched
#                            | / _---=> hardirq/softirq
#                            || / _--=> preempt-depth
#                            ||| /     delay
#           TASK-PID   CPU#  ||||    TIMESTAMP  FUNCTION
#              | |       |   ||||       |         |
```

Function tracer example (enabled)

```
# echo function >current_tracer; cat trace | head -13; echo nop >current_tracer
# tracer: function
#
# entries-in-buffer/entries-written: 1004455/1004455   #P:32
#
#                               _-----=> irqs-off
#                              / _----=> need-resched
#                             | / _---=> hardirq/softirq
#                             || / _--=> preempt-depth
#                             ||| /     delay
#           TASK-PID   CPU#  ||||    TIMESTAMP  FUNCTION
#              | |       |   ||||       |         |
           Timer-4636  [028] d... 139138.257037: do_syscall_64 <-entry_SYSCALL_64_after_hwframe
          <idle>-0     [029] d... 139138.257037: pm_qos_read_value <-cpuidle_governor_latency_req
          <idle>-0     [013] .... 139138.257037: sched_idle_set_state <-cpuidle_enter_state
          <idle>-0     [010] d... 139138.257038: tick_nohz_get_sleep_length <-menu_select
          <idle>-0     [009] d... 139138.257038: tick_check_broadcast_expired <-do_idle
          <idle>-0     [025] .... 139138.257038: sched_idle_set_state <-cpuidle_enter_state
          <idle>-0     [026] .... 139138.257038: sched_idle_set_state <-cpuidle_enter_state
```

Event tracer

Enable individual events:

```
# echo 1 >events/sched/sched_wakeup/enable
# echo 1 >events/sched/sched_wakeup_new/enable
```

Enable event group:

```
# echo 1 >events/sched/enable
```

Example:

```
# tracer: nop
#
# entries-in-buffer/entries-written: 1040906/12523426   #P:32
#
#                              _-----=> irqs-off
#                             / _----=> need-resched
#                            | / _---=> hardirq/softirq
#                            || / _--=> preempt-depth
#                            ||| /     delay
#           TASK-PID   CPU#  ||||    TIMESTAMP  FUNCTION
#              | |       |   ||||       |         |
          <idle>-0     [018] dNh. 139991.935902: sched_wakeup: comm=cyclictest pid=44772 prio=0
          <idle>-0     [018] dNh. 139991.936101: sched_wakeup: comm=cyclictest pid=44772 prio=0
          <idle>-0     [018] dNh. 139991.936302: sched_wakeup: comm=cyclictest pid=44772 prio=0
```

Printk tracer

Insert into kernel code:

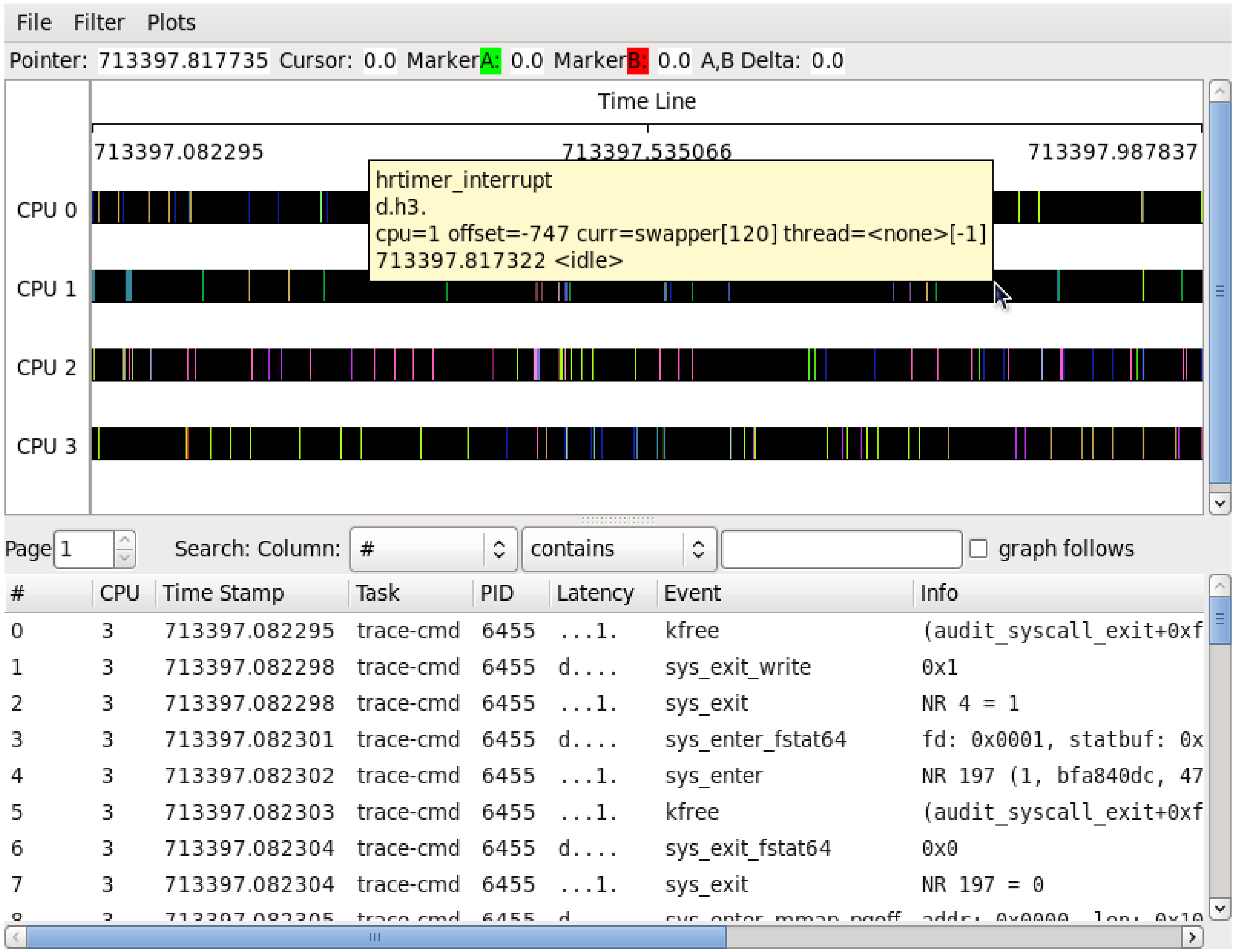
```
trace_printk(...);
```

Command line interface trace-cmd

For example: Enable all events:

```
trace-cmd record -e all
disable all
enable all
Hit Ctrl^C to stop recording
^Coffset=2aa000
offset=4d8000
offset=69c000
offset=8be000
Kernel buffer statistics: [..]
```

GUI kernelshark



```
hrtimer_interrupt
d.h3.
cpu=1 offset=-747 curr=swapper[120] thread=<none>[-1]
713397.817322 <idle>
```

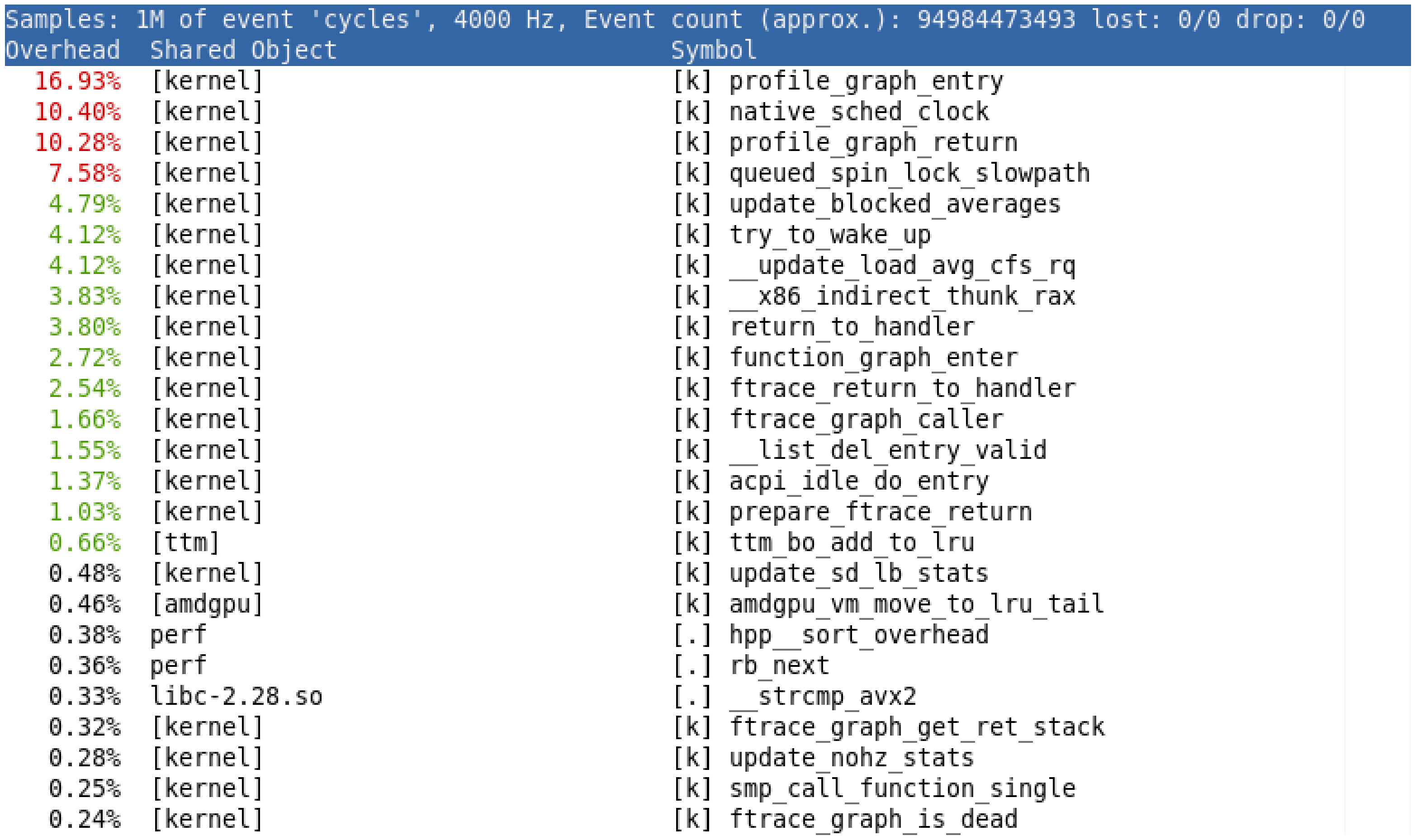
#	CPU	Time Stamp	Task	PID	Latency	Event	Info
0	3	713397.082295	trace-cmd	6455	...1.	kfree	(audit_syscall_exit+0xf
1	3	713397.082298	trace-cmd	6455	d....	sys_exit_write	0x1
2	3	713397.082298	trace-cmd	6455	...1.	sys_exit	NR 4 = 1
3	3	713397.082301	trace-cmd	6455	d....	sys_enter_fstat64	fd: 0x0001, statbuf: 0x
4	3	713397.082302	trace-cmd	6455	...1.	sys_enter	NR 197 (1, bfa840dc, 47
5	3	713397.082303	trace-cmd	6455	...1.	kfree	(audit_syscall_exit+0xf
6	3	713397.082304	trace-cmd	6455	d....	sys_exit_fstat64	0x0
7	3	713397.082304	trace-cmd	6455	...1.	sys_exit	NR 197 = 0
8	3	713397.082305	trace-cmd	6455	d....	sys_enter_mmap_pgoff	addr: 0x0000, len: 0x10

Performance tool „perf“

A single tool (*perf*) incorporates a number of various different funktions (similar to *git*):

```
cd tools/perf
make
make install

perf
The most commonly used perf commands are:
   annotate   Read perf.data (created by perf record) and display annotated code
   list       List all symbolic event types
   record     Run a command and record its profile into perf.data
   report     Read perf.data (created by perf record) and display the profile
   stat       Run a command and gather performance counter statistics
   top        System profiling tool.
```

perf top



```
Samples: 1M of event 'cycles', 4000 Hz, Event count (approx.): 94984473493 lost: 0/0 drop: 0/0
Overhead  Shared Object                                  Symbol
  16.93%  [kernel]                                       [k] profile_graph_entry
  10.40%  [kernel]                                       [k] native_sched_clock
  10.28%  [kernel]                                       [k] profile_graph_return
   7.58%  [kernel]                                       [k] queued_spin_lock_slowpath
   4.79%  [kernel]                                       [k] update_blocked_averages
   4.12%  [kernel]                                       [k] try_to_wake_up
   4.12%  [kernel]                                       [k] __update_load_avg_cfs_rq
   3.83%  [kernel]                                       [k] __x86_indirect_thunk_rax
   3.80%  [kernel]                                       [k] return_to_handler
   2.72%  [kernel]                                       [k] function_graph_enter
   2.54%  [kernel]                                       [k] ftrace_return_to_handler
   1.66%  [kernel]                                       [k] ftrace_graph_caller
   1.55%  [kernel]                                       [k] __list_del_entry_valid
   1.37%  [kernel]                                       [k] acpi_idle_do_entry
   1.03%  [kernel]                                       [k] prepare_ftrace_return
   0.66%  [ttm]                                          [k] ttm_bo_add_to_lru
   0.48%  [kernel]                                       [k] update_sd_lb_stats
   0.46%  [amdgpu]                                       [k] amdgpu_vm_move_to_lru_tail
   0.38%  perf                                           [.] hpp__sort_overhead
   0.36%  perf                                           [.] rb_next
   0.33%  libc-2.28.so                                   [.] __strcmp_avx2
   0.32%  [kernel]                                       [k] ftrace_graph_get_ret_stack
   0.28%  [kernel]                                       [k] update_nohz_stats
   0.25%  [kernel]                                       [k] smp_call_function_single
   0.24%  [kernel]                                       [k] ftrace_graph_is_dead
```

perf stat

Run a program and inspect the performance counters:

```
# perf stat sleep 1

 Performance counter stats for 'sleep 1':

          3.82 msec task-clock                #    0.004 CPUs utilized
            25      context-switches          #    0.007 M/sec
             0      cpu-migrations            #    0.000 K/sec
            63      page-faults               #    0.016 M/sec
    13,252,477      cycles                    #    3.465 GHz                      (78.71%)
     2,779,375      stalled-cycles-frontend   #   20.97% frontend cycles idle     (78.60%)
     1,109,240      stalled-cycles-backend    #    8.37% backend cycles idle      (80.42%)
     7,626,038      instructions              #    0.58  insn per cycle
                                              #    0.36  stalled cycles per insn  (78.44%)
     1,721,232      branches                  #  449.999 M/sec                    (99.24%)
        54,843      branch-misses             #    3.19% of all branches          (84.60%)

   1.007599675 seconds time elapsed

   0.000764000 seconds user
   0.005242000 seconds sys
```

perf stat (example busy loop)

Run a busy loop and inspect the performance counters under various real-time conditions:

```
int main(int argc, char *argv[])
{
  int cycles = 100000000;
  while (cycles--) ;
}
```

perf stat (example busy loop): no real-time

Run cyclictest in background, run a busy loop and inspect the performance counters (no real-time):

```
# perf stat ./busyloop

 Performance counter stats for './busyloop':

           213.97 msec task-clock                #    0.931 CPUs utilized
            1,381      context-switches          # 6483.568 M/sec
                0      cpu-migrations            #    0.000 K/sec
               49      page-faults               #  230.047 M/sec
      728,795,223      cycles                    # 3421573.817 GHz                (83.01%)
      521,429,641      stalled-cycles-frontend   #   71.55% frontend cycles idle     (83.35%)
      235,074,710      stalled-cycles-backend    #   32.26% backend cycles idle      (66.86%)
      512,846,836      instructions              #    0.70  insn per cycle
                                                 #    1.02  stalled cycles per insn  (83.41%)
      103,153,124      branches                  # 484286967.136 M/sec               (83.45%)
          144,844      branch-misses             #    0.14% of all branches          (83.33%)

      0.229856332 seconds time elapsed

      0.218521000 seconds user
      0.000954000 seconds sys
```

perf stat (real-time, no affinity)

Run cyclictest in background, run a busy loop and inspect the performance counters (real-time, no affinity):

```
# perf stat chrt -f 90 ./busyloop

 Performance counter stats for 'chrt -f 90 ./busyloop':

           213.82 msec task-clock                #    0.889 CPUs utilized
            2,397      context-switches          # 11253.521 M/sec
            2,392      cpu-migrations            # 11230.047 M/sec
              112      page-faults               #  525.822 M/sec
      723,177,255      cycles                    # 3395198.380 GHz                (83.34%)
      508,838,060      stalled-cycles-frontend   #   70.36% frontend cycles idle     (83.36%)
      226,652,203      stalled-cycles-backend    #   31.34% backend cycles idle      (66.69%)
      524,733,993      instructions              #    0.73  insn per cycle
                                                 #    0.97  stalled cycles per insn  (83.33%)
      106,182,724      branches                  # 498510441.315 M/sec            (83.36%)
          287,257      branch-misses             #    0.27% of all branches          (83.25%)

      0.240628157 seconds time elapsed

      0.223934000 seconds user
      0.000000000 seconds sys
```

perf stat (real-time, affinity)

Run cyclictest in background, run a busy loop and inspect the performance counters (no real-time, affinity):

```
# perf stat taskset -c 1 chrt -f 90 ./busyloop

 Performance counter stats for 'taskset -c 1 chrt -f 90 ./busyloop':

            209.14 msec task-clock                #    0.944 CPUs utilized
             1,108      context-switches          # 5301.435 M/sec
                 1      cpu-migrations            #    4.785 M/sec
               182      page-faults               #  870.813 M/sec
       713,360,124      cycles                    # 3413206.335 GHz                   (83.28%)
       506,002,912      stalled-cycles-frontend   #   70.93% frontend cycles idle     (83.29%)
       107,863,334      stalled-cycles-backend    #   15.12% backend cycles idle      (66.51%)
       513,113,816      instructions              #    0.72  insn per cycle
                                                  #    0.99  stalled cycles per insn  (83.24%)
       103,119,288      branches                  # 493393722.488 M/sec               (83.29%)
           137,694      branch-misses             #    0.13% of all branches          (83.63%)

       0.221539588 seconds time elapsed

       0.212750000 seconds user
       0.000967000 seconds sys
```

perf stat (high prio real-time, affinity)

Run cyclictest in background, run a busy loop and inspect the performance counters (no real-time with same priority as cyclictest, affinity):

```
# perf stat taskset -c 1 chrt -f 99 ./busyloop

 Performance counter stats for 'taskset -c 1 chrt -f 99 ./busyloop':

            215.96 msec task-clock                #    0.998 CPUs utilized
                 9      context-switches          #   41.860 M/sec
                 1      cpu-migrations            #    4.651 M/sec
               183      page-faults               #  851.163 M/sec
       742,475,874      cycles                    # 3453376.158 GHz                 (83.38%)
       539,580,837      stalled-cycles-frontend   #   72.67% frontend cycles idle     (83.34%)
       113,773,162      stalled-cycles-backend    #   15.32% backend cycles idle      (66.67%)
       504,496,302      instructions              #    0.68  insn per cycle
                                                  #    1.07  stalled cycles per insn  (83.33%)
       101,077,428      branches                  # 470127572.093 M/sec               (83.33%)
            38,413      branch-misses             #    0.04% of all branches          (83.28%)

       0.216494299 seconds time elapsed

       0.214388000 seconds user
       0.002003000 seconds sys
```

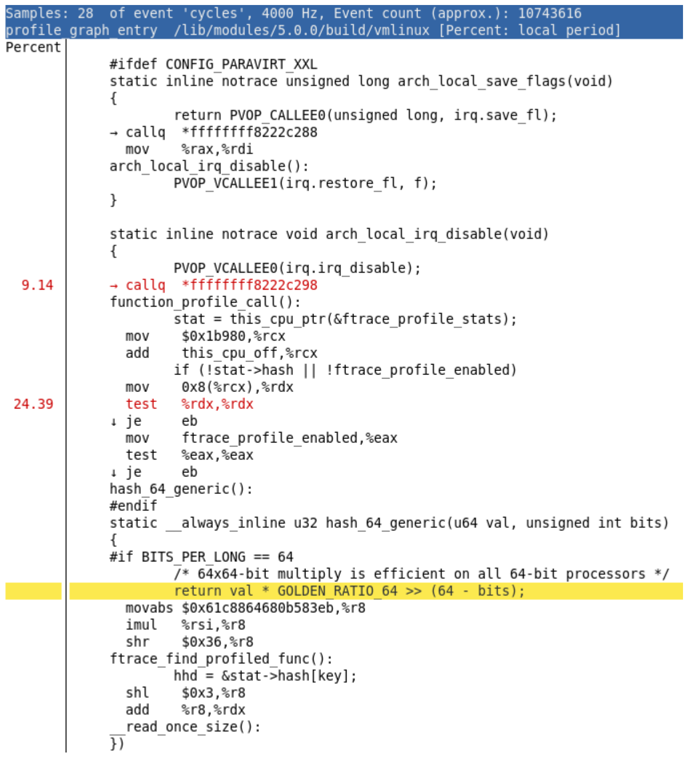
perf record/annotate

Data capturing:

```
# perf record sleep 1
[ perf record: Woken up 1 times to write data ]
[ perf record: Captured and wrote 0.015 MB perf.data (28 samples) ]
```

Data analysis:

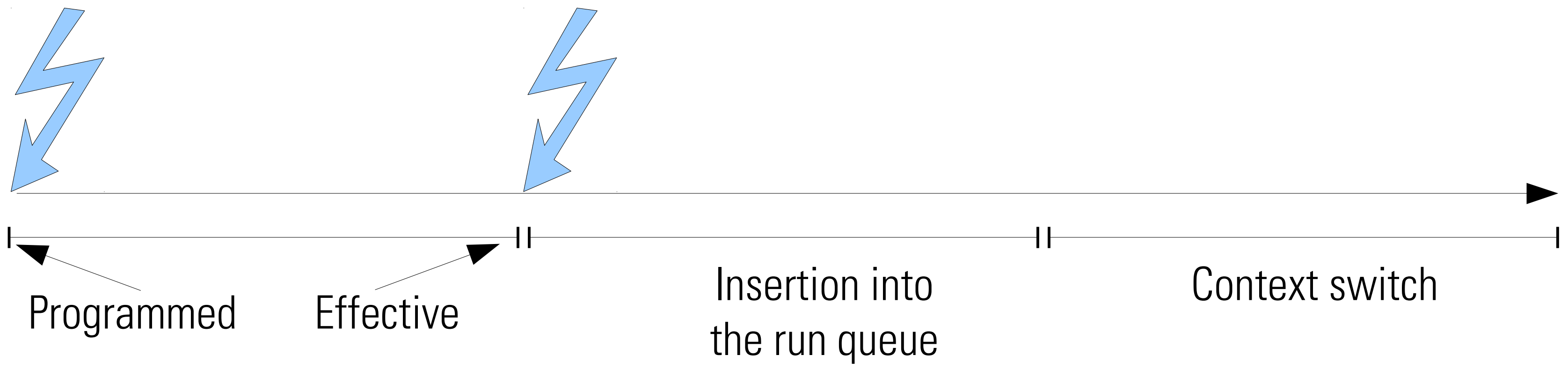
```
perf annotate
```



```
Samples: 28  of event 'cycles', 4000 Hz, Event count (approx.): 10743616
profile_graph_entry  /lib/modules/5.0.0/build/vmlinux [Percent: local period]
Percent│
       │      #ifdef CONFIG_PARAVIRT_XXL
       │      static inline notrace unsigned long arch_local_save_flags(void)
       │      {
       │              return PVOP_CALLEE0(unsigned long, irq.save_fl);
       │      → callq  *ffffffff8222c288
       │        mov    %rax,%rdi
       │      arch_local_irq_disable():
       │              PVOP_VCALLEE1(irq.restore_fl, f);
       │      }
       │
       │      static inline notrace void arch_local_irq_disable(void)
       │      {
       │              PVOP_VCALLEE0(irq.irq_disable);
  9.14 │      → callq  *ffffffff8222c298
       │      function_profile_call():
       │              stat = this_cpu_ptr(&ftrace_profile_stats);
       │        mov    $0x1b980,%rcx
       │        add    this_cpu_off,%rcx
       │              if (!stat->hash || !ftrace_profile_enabled)
       │        mov    0x8(%rcx),%rdx
 24.39 │        test   %rdx,%rdx
       │      ↓ je     eb
       │        mov    ftrace_profile_enabled,%eax
       │        test   %eax,%eax
       │      ↓ je     eb
       │      hash_64_generic():
       │      #endif
       │      static __always_inline u32 hash_64_generic(u64 val, unsigned int bits)
       │      {
       │      #if BITS_PER_LONG == 64
       │              /* 64x64-bit multiply is efficient on all 64-bit processors */
       │              return val * GOLDEN_RATIO_64 >> (64 - bits);
       │        movabs $0x61c8864680b583eb,%r8
       │        imul   %rsi,%r8
       │        shr    $0x36,%r8
       │      ftrace_find_profiled_func():
       │              hhd = &stat->hash[key];
       │        shl    $0x3,%r8
       │        add    %r8,%rdx
       │      __read_once_size():
       │      })
```

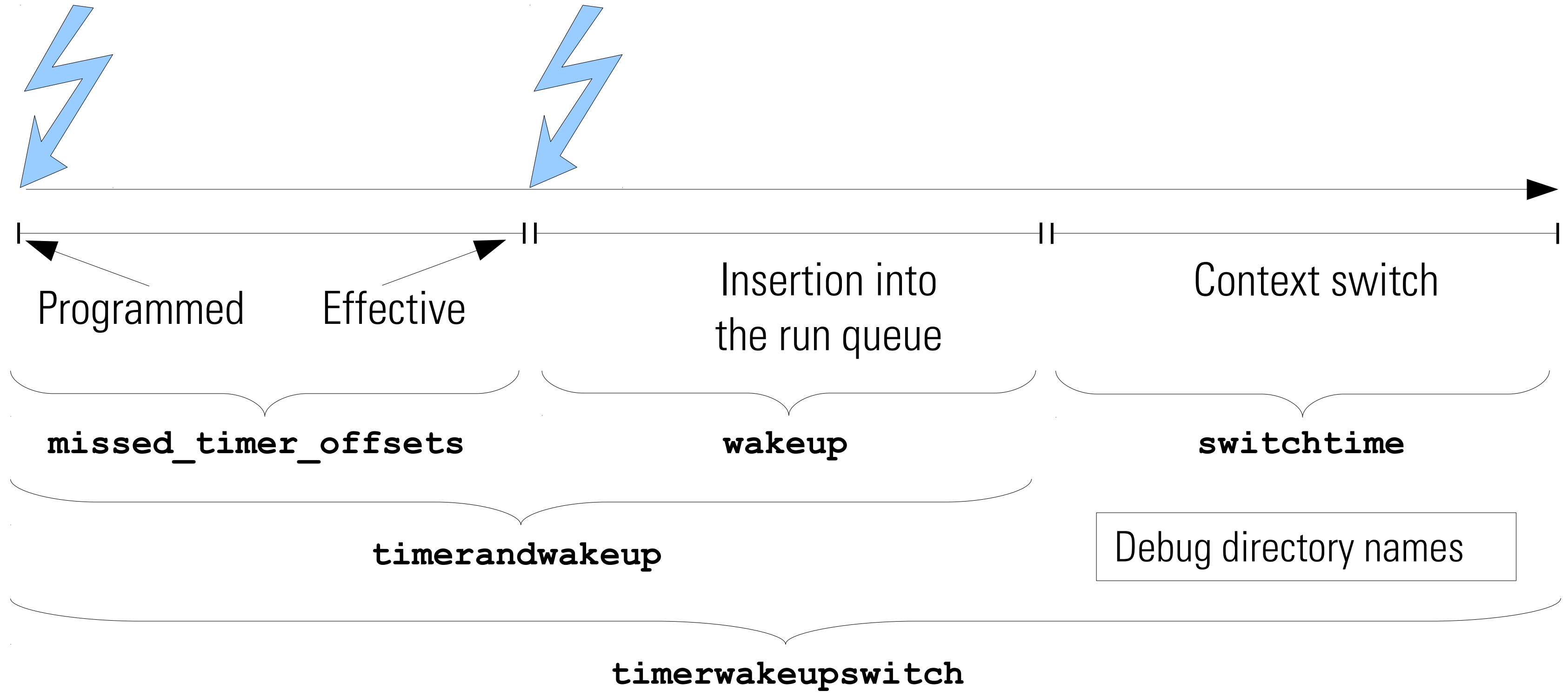
Internal recording of effective latencies, sections

Restarting a waiting application by timer expiration



Internal recording of effective latencies, variables

Restarting a waiting application by timer expiration



Internal recording of effective latencies, access

Kernel configuration

```
CONFIG_WAKEUP_LATENCY_HIST=y
CONFIG_MISSED_TIMER_OFFSET_HIST=y
CONFIG_SWITCHTIME_HIST=y
```

Directory

```
/sys/kernel/debug/latency_hist
```

Directory in earlier kernel versions

```
/sys/kernel/debug/tracing/latency_hist
```

Important subdirectories

```
/sys/kernel/debug/latency_hist/enable
/sys/kernel/debug/latency_hist/wakeup
/sys/kernel/debug/latency_hist/missed_timer_offsets
/sys/kernel/debug/latency_hist/timerandwakeup
/sys/kernel/debug/latency_hist/switchtime
/sys/kernel/debug/latency_hist/timerwakeupswitch
```

Access via virtual debug filesystem

Single command

```
mount -t debugfs nodev /sys/kernel/debug
```

Permanent configuration in `/etc/fstab`

```
nodev /sys/kernel/debug debugfs defaults 0 0
```

Internal recording of effective latencies, management

Files

Enable internal recording of effective latencies

```
echo 1 >/sys/kernel/debug/latency_hist/enable/wakeup
echo 1 >/sys/kernel/debug/latency_hist/enable/missed_timer_offsets
echo 1 >/sys/kernel/debug/latency_hist/enable/timerandwakeup
echo 1 >/sys/kernel/debug/latency_hist/enable/switchtime
echo 1 >/sys/kernel/debug/latency_hist/enable/timerwakeupswitch
```

Histograms of latency data

```
/sys/kernel/debug/latency_hist/wakeup/CPU*
/sys/kernel/debug/latency_hist/missed_timer_offsets/CPU*
/sys/kernel/debug/latency_hist/timerandwakeup/CPU*
/sys/kernel/debug/latency_hist/switchtime/CPU*
/sys/kernel/debug/latency_hist/timerwakeupswitch/CPU*
```

Histograms of latency data

Data

```
grep -v " 0$" /sys/kernel/debug/latency_hist/timerwakeupswitch/CPU0
#Minimum latency: 0 microseconds
#Average latency: 0 microseconds
#Maximum latency: 40 microseconds
#Total samples: 1457599
#There are 0 samples greater or equal than 10240 microseconds.
#usecs             samples
     0             1452538
     1                3323
     2                1676
     3                  11
     4                   3
     5                  17
     6                  10
     7                   5
     8                   2
```

Hints to culprit and victim

Files

Enable internal recording of effective latencies

```
echo 1 >/sys/kernel/debug/latency_hist/enable/wakeup
echo 1 >/sys/kernel/debug/latency_hist/enable/missed_timer_offsets
echo 1 >/sys/kernel/debug/latency_hist/enable/timerandwakeup
echo 1 >/sys/kernel/debug/latency_hist/enable/switchtime
echo 1 >/sys/kernel/debug/latency_hist/enable/timerwakeupswitch
```

Histograms of latency data

```
/sys/kernel/debug/latency_hist/wakeup/CPU*
/sys/kernel/debug/latency_hist/missed_timer_offsets/CPU*
/sys/kernel/debug/latency_hist/timerandwakeup/CPU*
/sys/kernel/debug/latency_hist/switchtime/CPU*
/sys/kernel/debug/latency_hist/timerwakeupswitch/CPU*
```

Hints to culprit and victim in case of a prolonged latency

```
/sys/kernel/debug/latency_hist/wakeup/max_latency-CPU*
/sys/kernel/debug/latency_hist/missed_timer_offsets/max_latency-CPU*
/sys/kernel/debug/latency_hist/timerandwakeup/max_latency-CPU*
/sys/kernel/debug/latency_hist/switchtime/max_latency-CPU*
/sys/kernel/debug/latency_hist/timerwakeupswitch/max_latency-CPU*
```

Hints to culprit and victim in case of a prolonged latency

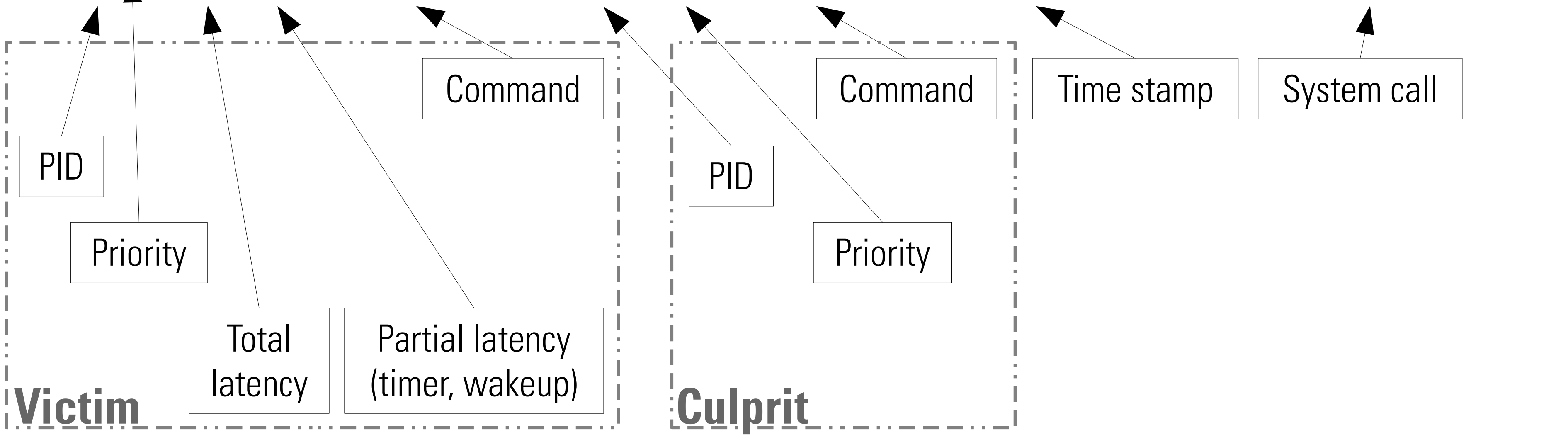
Characteristic data of the highest scheduling latency since the most recent reset (reset occurs every 5 minutes at the OSADL QA Farm):

```
# cat /sys/kernel/debug/latency_hist/timerwakeupswitch/max_latency-CPU0
23579 99 8 (7,0) cyclictest <- 22176 -19 bandwidth64 3522647.050475 __x64_sys_clock_nanosleep
```

Hints to culprit and victim in case of a prolonged latency

Characteristic data of the highest scheduling latency since the most recent reset (reset occurs every 5 minutes at the OSADL QA Farm):

```
# cat /sys/kernel/debug/latency_hist/timerwakeupswitch/max_latency-CPU0
23579 99 8 (7,0) cyclictest <- 22176 -19 bandwidth64 3522647.050475 __x64_sys_clock_nanosleep
```



Handle histograms - Reset

Reset

```
#!/bin/bash

HISTDIR=/sys/kernel/debug/latency_hist

if test -d $HISTDIR
then
  cd $HISTDIR
  for i in `find . | grep /reset$`
  do
    echo 1 >$i
  done
fi
```

Calibration of latency recording (1)

“Bad” driver (blocksys.ko)

```
  local_irq_disable();
  while (nops--)
    asm("nop");
  local_irq_enable();
```

Using the “bad” driver (mklatency)

Command

```
    ./mklatency
```

Or

```
    echo 1000000 >/dev/blocksys
```

Kernel log

```
# dmesg | tail -2
[231234.857241] blocksys: preemption and interrupts of CPU #6 will be blocked for 1000000 nops
[231234.876478] blocksys: preemption and interrupts of CPU #6 blocked for about 2146 us
```

Culprit/victim output

```
# cat max_latency-CPU6
4122437 99 2087 (2081,5) cyclictest <- 4122293 -21 bash 231235.023676 __x64_sys_clock_nanosleep
```

Calibration of latency recording (2)

Output of cyclictest

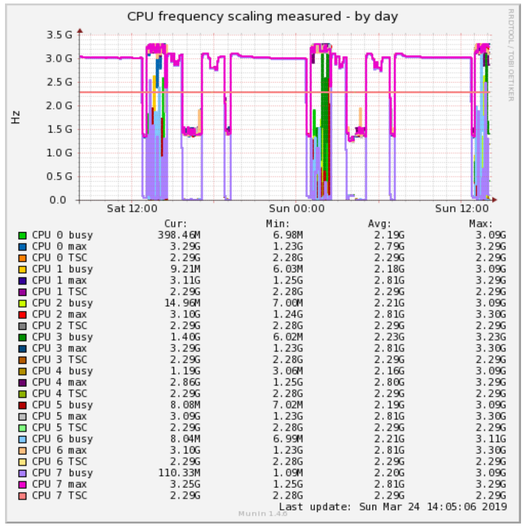
```
# cyclictest -m -n -Sp90 -i100 -d0
# /dev/cpu_dma_latency set to 0us
policy: fifo: loadavg: 10.43 6.56 3.38 2/1454 4126098

T: 0 (4122431) P:99 I:100 C:5154828 Min:      3 Act:    4 Avg:    6 Max:      42
T: 1 (4122432) P:99 I:100 C:5154687 Min:      3 Act:    4 Avg:    5 Max:      88
T: 2 (4122433) P:99 I:100 C:5154561 Min:      3 Act:    4 Avg:    5 Max:      40
T: 3 (4122434) P:99 I:100 C:5154439 Min:      3 Act:    7 Avg:    6 Max:      40
T: 4 (4122435) P:99 I:100 C:5154318 Min:      3 Act:    4 Avg:    6 Max:      31
T: 5 (4122436) P:99 I:100 C:5154196 Min:      3 Act:    5 Avg:    5 Max:      47
T: 6 (4122437) P:99 I:100 C:5153993 Min:      3 Act:    4 Avg:    6 Max:    2091
T: 7 (4122438) P:99 I:100 C:5153936 Min:      3 Act:    4 Avg:    5 Max:      94
T: 8 (4122439) P:99 I:100 C:5153807 Min:      3 Act:    4 Avg:    5 Max:      39
T: 9 (4122440) P:99 I:100 C:5153662 Min:      3 Act:    5 Avg:    5 Max:      51
T:10 (4122441) P:99 I:100 C:5153517 Min:      3 Act:    5 Avg:    5 Max:      42
T:11 (4122442) P:99 I:100 C:5153371 Min:      3 Act:    4 Avg:    5 Max:      30
```

Calibration of latency recording (2)

Output of cyclictest

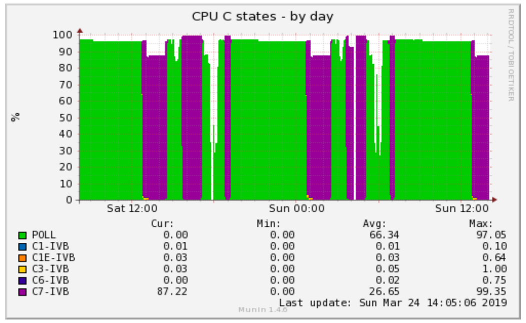
```
# cyclictest -m -n -Sp90 -i100 -d0
# /dev/cpu_dma_latency set to 0us
policy: fifo: loadavg: 10.43 6.56 3.38 2/1454 4126098

T: 0 (4122431) P:99 I:100 C:5154828 Min:      3 Act:    4 Avg:    6 Max:      42
T: 1 (4122432) P:99 I:100 C:5154687 Min:      3 Act:    4 Avg:    5 Max:      88
T: 2 (4122433) P:99 I:100 C:5154561 Min:      3 Act:    4 Avg:    5 Max:      40
T: 3 (4122434) P:99 I:100 C:5154439 Min:      3 Act:    7 Avg:    6 Max:      40
T: 4 (4122435) P:99 I:100 C:5154318 Min:      3 Act:    4 Avg:    6 Max:      31
T: 5 (4122436) P:99 I:100 C:5154196 Min:      3 Act:    5 Avg:    5 Max:      47
T: 6 (4122437) P:99 I:100 C:5153993 Min:      3 Act:    4 Avg:    6 Max:    2091
T: 7 (4122438) P:99 I:100 C:5153936 Min:      3 Act:    4 Avg:    5 Max:      94
T: 8 (4122439) P:99 I:100 C:5153807 Min:      3 Act:    4 Avg:    5 Max:      39
T: 9 (4122440) P:99 I:100 C:5153662 Min:      3 Act:    5 Avg:    5 Max:      51
T:10 (4122441) P:99 I:100 C:5153517 Min:      3 Act:    5 Avg:    5 Max:      42
T:11 (4122442) P:99 I:100 C:5153371 Min:      3 Act:    4 Avg:    5 Max:      30
```

Continuous recording of real-time related system variables



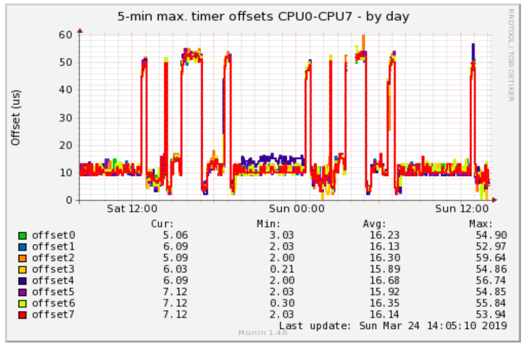
	Cur:	Min:	Avg:	Max:
🟩 CPU 0 busy	398.46M	6.98M	2.19G	3.09G
🟦 CPU 0 max	3.29G	1.23G	2.79G	3.29G
🟧 CPU 0 TSC	2.29G	2.28G	2.29G	2.29G
🟨 CPU 1 busy	9.21M	6.03M	2.18G	3.09G
🟦 CPU 1 max	3.11G	1.25G	2.81G	3.29G
🟪 CPU 1 TSC	2.29G	2.28G	2.29G	2.29G
🟨 CPU 2 busy	14.96M	7.00M	2.21G	3.09G
🟥 CPU 2 max	3.10G	1.24G	2.81G	3.30G
⬛ CPU 2 TSC	2.29G	2.28G	2.29G	2.29G
🟩 CPU 3 busy	1.40G	6.02M	2.23G	3.23G
🟦 CPU 3 max	3.29G	1.23G	2.81G	3.30G
🟫 CPU 3 TSC	2.29G	2.28G	2.29G	2.29G
🟫 CPU 4 busy	1.19G	3.06M	2.16G	3.09G
🟪 CPU 4 max	2.86G	1.25G	2.80G	3.29G
🟩 CPU 4 TSC	2.29G	2.28G	2.29G	2.29G
🟥 CPU 5 busy	8.08M	7.02M	2.19G	3.09G
⬜ CPU 5 max	3.09G	1.23G	2.81G	3.30G
🟩 CPU 5 TSC	2.29G	2.28G	2.29G	2.29G
🟦 CPU 6 busy	8.04M	6.99M	2.21G	3.11G
🟧 CPU 6 max	3.10G	1.23G	2.81G	3.30G
🟨 CPU 6 TSC	2.29G	2.28G	2.29G	2.29G
🟪 CPU 7 busy	110.33M	1.09M	2.20G	3.09G
🟪 CPU 7 max	3.25G	1.25G	2.81G	3.29G
🟥 CPU 7 TSC	2.29G	2.28G	2.29G	2.29G

Last update: Sun Mar 24 14:05:06 2019



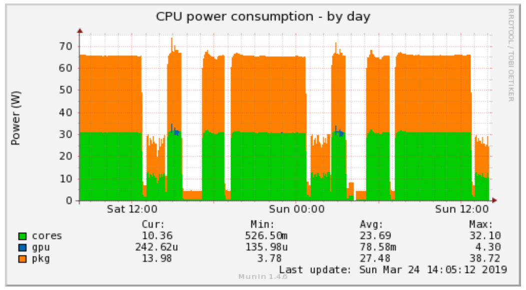
	Cur:	Min:	Avg:	Max:
🟩 POLL	0.00	0.00	66.34	97.05
🟦 C1-IVB	0.01	0.00	0.01	0.10
🟧 C1E-IVB	0.03	0.00	0.03	0.64
🟨 C3-IVB	0.03	0.00	0.05	1.00
🟦 C6-IVB	0.00	0.00	0.02	0.75
🟪 C7-IVB	87.22	0.00	26.65	99.35

Last update: Sun Mar 24 14:05:06 2019



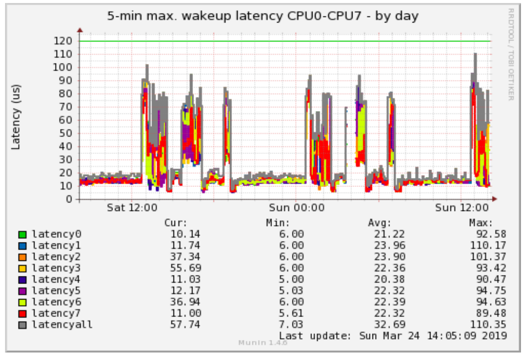
	Cur:	Min:	Avg:	Max:
🟩 offset0	5.06	3.03	16.23	54.90
🟦 offset1	6.09	2.03	16.13	52.97
🟧 offset2	5.09	2.00	16.30	59.64
🟨 offset3	6.03	0.21	15.89	54.86
🟦 offset4	6.09	2.00	16.68	56.74
🟪 offset5	7.12	2.03	15.92	54.85
🟨 offset6	7.12	0.30	16.35	55.84
🟥 offset7	7.12	2.03	16.14	53.94

Last update: Sun Mar 24 14:05:10 2019



	Cur:	Min:	Avg:	Max:
🟩 cores	10.36	526.50m	23.69	32.10
🟦 gpu	242.62u	135.98u	78.58m	4.30
🟧 pkg	13.98	3.78	27.48	38.72

Last update: Sun Mar 24 14:05:12 2019

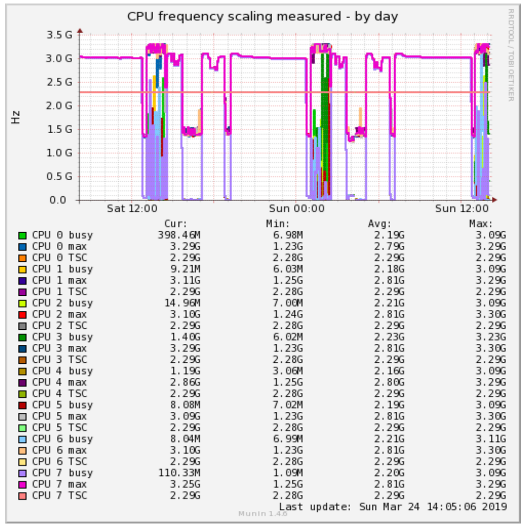


	Cur:	Min:	Avg:	Max:
🟩 latency0	10.14	6.00	21.22	92.58
🟦 latency1	11.74	6.00	23.96	110.17
🟧 latency2	37.34	6.00	23.90	101.37
🟨 latency3	55.69	6.00	22.36	93.42
🟦 latency4	11.03	5.00	20.38	90.47
🟪 latency5	12.17	5.03	22.32	94.75
🟨 latency6	36.94	6.00	22.39	94.63
🟥 latency7	11.00	5.61	22.32	89.48
⬛ latencyall	57.74	7.03	32.69	110.35

Last update: Sun Mar 24 14:05:09 2019

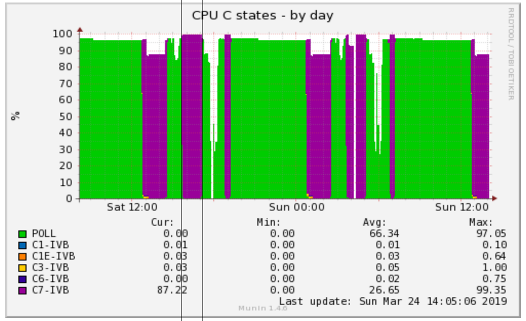
Using the *Munin* monitoring tool equipped with additional plugins

Continuous recording of real-time related system variables



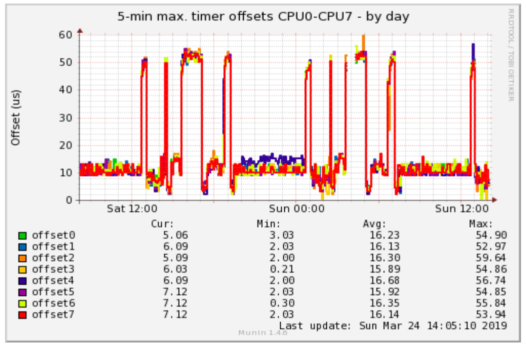
	Cur:	Min:	Avg:	Max:
🟩 CPU 0 busy	398.46M	6.98M	2.19G	3.09G
🟦 CPU 0 max	3.29G	1.23G	2.79G	3.29G
🟧 CPU 0 TSC	2.29G	2.28G	2.29G	2.29G
🟨 CPU 1 busy	9.21M	6.03M	2.18G	3.09G
🟦 CPU 1 max	3.11G	1.25G	2.81G	3.29G
🟪 CPU 1 TSC	2.29G	2.28G	2.29G	2.29G
🟩 CPU 2 busy	14.96M	7.00M	2.21G	3.09G
🟥 CPU 2 max	3.10G	1.24G	2.81G	3.30G
⬛ CPU 2 TSC	2.29G	2.28G	2.29G	2.29G
🟩 CPU 3 busy	1.40G	6.02M	2.23G	3.23G
🟦 CPU 3 max	3.29G	1.23G	2.81G	3.30G
🟫 CPU 3 TSC	2.29G	2.28G	2.29G	2.29G
🟫 CPU 4 busy	1.19G	3.06M	2.16G	3.09G
🟪 CPU 4 max	2.86G	1.25G	2.80G	3.29G
🟩 CPU 4 TSC	2.29G	2.28G	2.29G	2.29G
🟥 CPU 5 busy	8.08M	7.02M	2.19G	3.09G
⬜ CPU 5 max	3.09G	1.23G	2.81G	3.30G
🟩 CPU 5 TSC	2.29G	2.28G	2.29G	2.29G
🟦 CPU 6 busy	8.04M	6.99M	2.21G	3.11G
🟧 CPU 6 max	3.10G	1.23G	2.81G	3.30G
🟨 CPU 6 TSC	2.29G	2.28G	2.29G	2.29G
🟪 CPU 7 busy	110.33M	1.09M	2.20G	3.09G
🟪 CPU 7 max	3.25G	1.25G	2.81G	3.29G
🟥 CPU 7 TSC	2.29G	2.28G	2.29G	2.29G

Last update: Sun Mar 24 14:05:06 2019



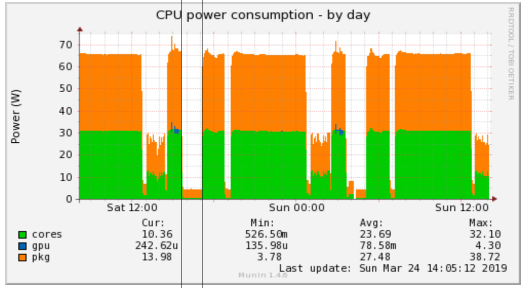
	Cur:	Min:	Avg:	Max:
🟩 POLL	0.00	0.00	66.34	97.05
🟦 C1-IVB	0.01	0.00	0.01	0.10
🟧 C1E-IVB	0.03	0.00	0.03	0.64
🟨 C3-IVB	0.03	0.00	0.05	1.00
🟦 C6-IVB	0.00	0.00	0.02	0.75
🟪 C7-IVB	87.22	0.00	26.65	99.35

Last update: Sun Mar 24 14:05:06 2019



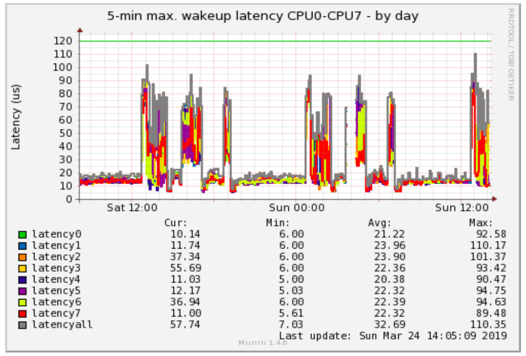
	Cur:	Min:	Avg:	Max:
🟩 offset0	5.06	3.03	16.23	54.90
🟦 offset1	6.09	2.03	16.13	52.97
🟧 offset2	5.09	2.00	16.30	59.64
🟨 offset3	6.03	0.21	15.89	54.86
🟦 offset4	6.09	2.00	16.68	56.74
🟪 offset5	7.12	2.03	15.92	54.85
🟩 offset6	7.12	0.30	16.35	55.84
🟥 offset7	7.12	2.03	16.14	53.94

Last update: Sun Mar 24 14:05:10 2019



	Cur:	Min:	Avg:	Max:
🟩 cores	10.36	526.50m	23.69	32.10
🟦 gpu	242.62u	135.98u	78.58m	4.30
🟧 pkg	13.98	3.78	27.48	38.72

Last update: Sun Mar 24 14:05:12 2019



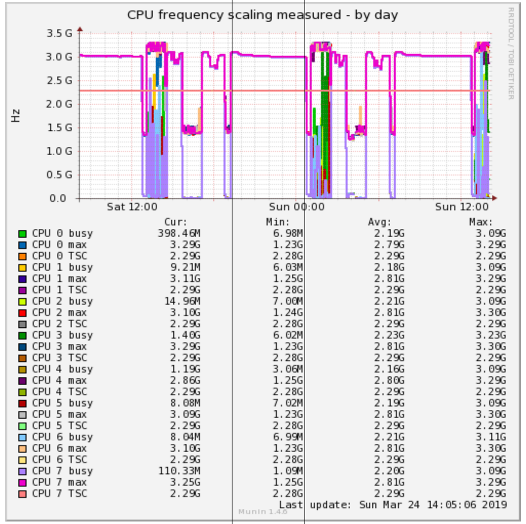
	Cur:	Min:	Avg:	Max:
🟩 latency0	10.14	6.00	21.22	92.58
🟦 latency1	11.74	6.00	23.96	110.17
🟧 latency2	37.34	6.00	23.90	101.37
🟨 latency3	55.69	6.00	22.36	93.42
🟦 latency4	11.03	5.00	20.38	90.47
🟪 latency5	12.17	5.03	22.32	94.75
🟩 latency6	36.94	6.00	22.39	94.63
🟥 latency7	11.00	5.61	22.32	89.48
⬛ latencyall	57.74	7.03	32.69	110.35

Last update: Sun Mar 24 14:05:09 2019

Temporal relationship between C states and power consumption

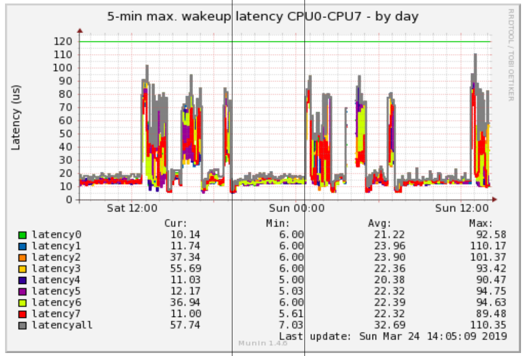
Using the *Munin* monitoring tool equipped with additional plugins

Compare real-time data to frequency modulation



	Cur:	Min:	Avg:	Max:
🟩 CPU 0 busy	398.46M	6.98M	2.19G	3.09G
🟦 CPU 0 max	3.29G	1.23G	2.79G	3.29G
🟧 CPU 0 TSC	2.29G	2.28G	2.29G	2.29G
🟨 CPU 1 busy	9.21M	6.03M	2.18G	3.09G
🟦 CPU 1 max	3.11G	1.25G	2.81G	3.29G
🟪 CPU 1 TSC	2.29G	2.28G	2.29G	2.29G
🟩 CPU 2 busy	14.96M	7.00M	2.21G	3.09G
🟥 CPU 2 max	3.10G	1.24G	2.81G	3.30G
⬛ CPU 2 TSC	2.29G	2.28G	2.29G	2.29G
🟩 CPU 3 busy	1.40G	6.02M	2.23G	3.23G
🟦 CPU 3 max	3.29G	1.23G	2.81G	3.30G
🟫 CPU 3 TSC	2.29G	2.28G	2.29G	2.29G
🟨 CPU 4 busy	1.19G	3.06M	2.16G	3.09G
🟪 CPU 4 max	2.86G	1.25G	2.80G	3.29G
🟩 CPU 4 TSC	2.29G	2.28G	2.29G	2.29G
🟥 CPU 5 busy	8.08M	7.02M	2.19G	3.09G
⬜ CPU 5 max	3.09G	1.23G	2.81G	3.30G
🟩 CPU 5 TSC	2.29G	2.28G	2.29G	2.29G
🟦 CPU 6 busy	8.04M	6.99M	2.21G	3.11G
🟧 CPU 6 max	3.10G	1.23G	2.81G	3.30G
🟨 CPU 6 TSC	2.29G	2.28G	2.29G	2.29G
🟪 CPU 7 busy	110.33M	1.09M	2.20G	3.09G
🟪 CPU 7 max	3.25G	1.25G	2.81G	3.29G
🟥 CPU 7 TSC	2.29G	2.28G	2.29G	2.29G

Last update: Sun Mar 24 14:05:06 2019

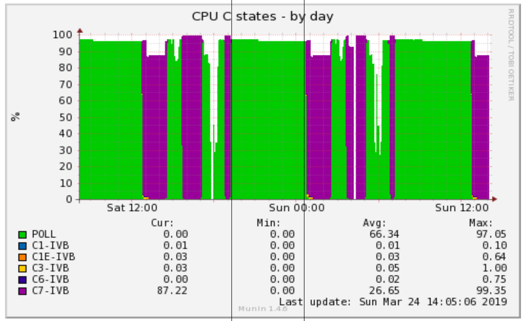


	Cur:	Min:	Avg:	Max:
🟩 latency0	10.14	6.00	21.22	92.58
🟦 latency1	11.74	6.00	23.96	110.17
🟧 latency2	37.34	6.00	23.90	101.37
🟨 latency3	55.69	6.00	22.36	93.42
🟦 latency4	11.03	5.00	20.38	90.47
🟪 latency5	12.17	5.03	22.32	94.75
🟩 latency6	36.94	6.00	22.39	94.63
🟥 latency7	11.00	5.61	22.32	89.48
⬛ latencyall	57.74	7.03	32.69	110.35

Last update: Sun Mar 24 14:05:09 2019

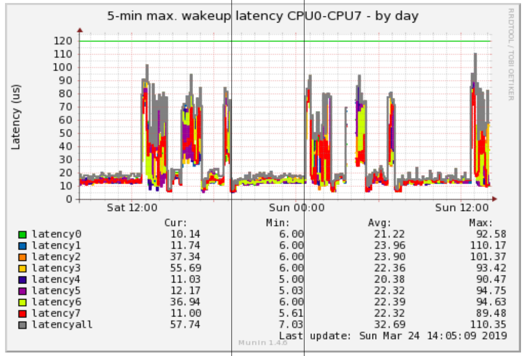
Frequency modulation disabled
leads to minimum latency

Compare real-time data to sleep stages



	Cur:	Min:	Avg:	Max:
🟩 POLL	0.00	0.00	66.34	97.05
🟦 C1-IVB	0.01	0.00	0.01	0.10
🟧 C1E-IVB	0.03	0.00	0.03	0.64
🟨 C3-IVB	0.03	0.00	0.05	1.00
🟦 C6-IVB	0.00	0.00	0.02	0.75
🟪 C7-IVB	87.22	0.00	26.65	99.35

Last update: Sun Mar 24 14:05:06 2019

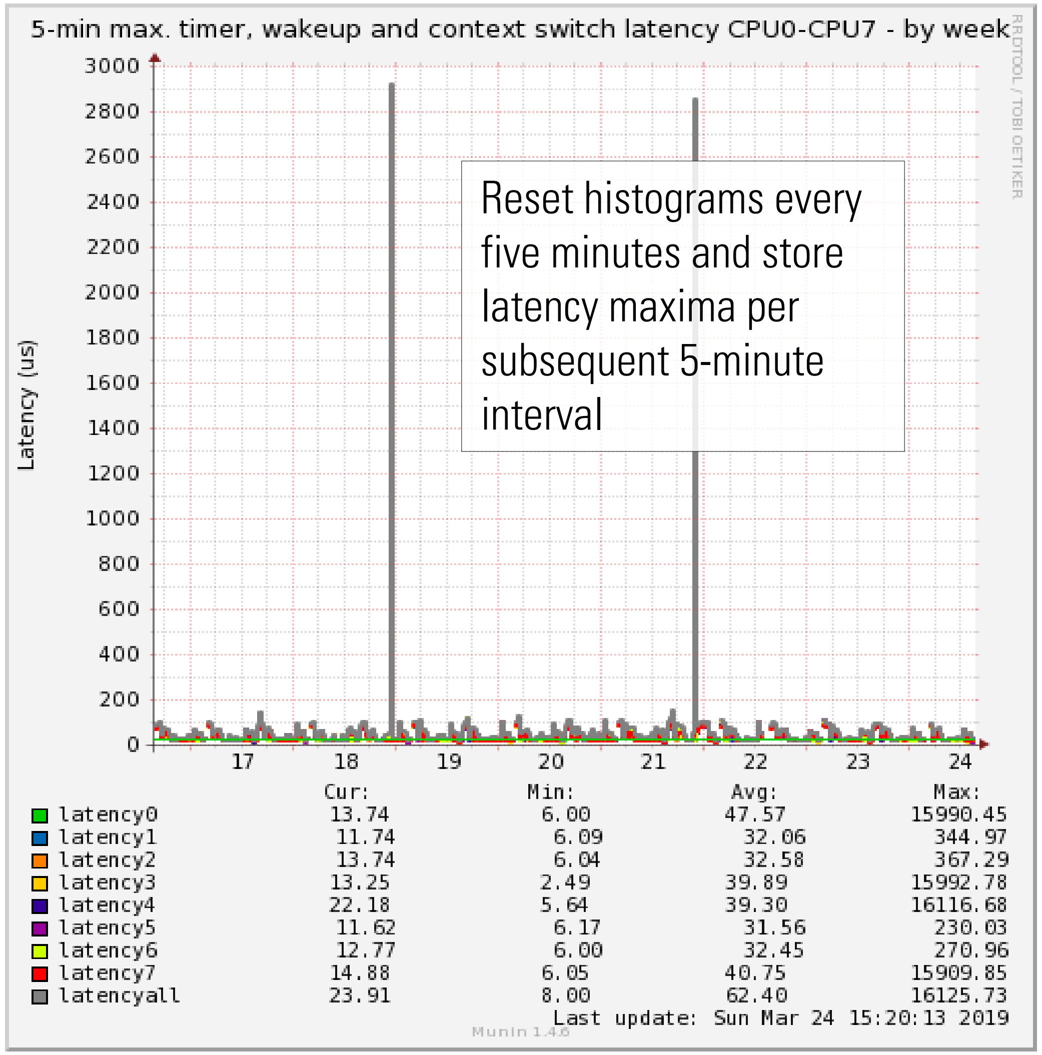


	Cur:	Min:	Avg:	Max:
🟩 latency0	10.14	6.00	21.22	92.58
🟦 latency1	11.74	6.00	23.96	110.17
🟧 latency2	37.34	6.00	23.90	101.37
🟨 latency3	55.69	6.00	22.36	93.42
🟦 latency4	11.03	5.00	20.38	90.47
🟪 latency5	12.17	5.03	22.32	94.75
🟩 latency6	36.94	6.00	22.39	94.63
🟥 latency7	11.00	5.61	22.32	89.48
⬜ latencyall	57.74	7.03	32.69	110.35

Last update: Sun Mar 24 14:05:09 2019

Sleep stages disabled (polling)
leads to minimum latency

Regain timing information that normally is lost in histograms



Reset histograms every five minutes and store latency maxima per subsequent 5-minute interval

	Cur:	Min:	Avg:	Max:
🟩 latency0	13.74	6.00	47.57	15990.45
🟦 latency1	11.74	6.09	32.06	344.97
🟧 latency2	13.74	6.04	32.58	367.29
🟨 latency3	13.25	2.49	39.89	15992.78
🟪 latency4	22.18	5.64	39.30	16116.68
🟪 latency5	11.62	6.17	31.56	230.03
🟨 latency6	12.77	6.00	32.45	270.96
🟥 latency7	14.88	6.05	40.75	15909.85
⬛ latencyall	23.91	8.00	62.40	16125.73

Last update: Sun Mar 24 15:20:13 2019