ftrace

dem Kernel bei der Arbeit zusehen

Chemnitzer Linux-Tage
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Goals of this talk

- hands-on introduction to ftrace
  - examples not only for developers
- encourage you to try ftrace
- make you remember ftrace next time you debug a problem

About me

- Codasip (www.codasip.com)
  - Linux Kernel on RISC-V
  - CHERI (www.cheri-linux.org)
- past
  - Linux Kernel on ARM (i.MX)
  - RFID (ISO 14443)
  - Wireshark
- www.kaiser.cx

ftrace

- tracing framework for the Linux Kernel
- started in 2008, not frequently used (I think)
- function calls
- events
- ringbuffer

design goals

- minimum overhead
  - kernel with ftrace support, tracing disabled
  - distro kernels support ftrace
- require no additional tools
  - only echo, cat

tracefs

- pseudo filesystem, similar to sysfs
- /sys/kernel/tracing/

current_tracer	select a tracer
tracing_on	enable/disable tracing
trace, trace_pipe	the ringbuffer
README	documentation

- files to configure filters, options
  - options modify the behaviour of tracers

function tracer

- intercept and trace function calls
- which functions can be traced?
  - /sys/kernel/tracing/available_filter_functions
- functions that can’t be traced
  - inline functions
  - functions that implement tracing
  - functions that are called very early at startup

function tracer (II)

```
[root@nb282 ~]# cd /sys/kernel/tracing/
[root@nb282 tracing]# echo function > current_tracer
[root@nb282 tracing]# echo 1 > tracing_on
[root@nb282 tracing]# echo 0 > tracing_on
[root@nb282 tracing]# head -12 trace
# tracer: function
#
#                              _-----=> irqs-off
#                             / _----=> need-resched
#                            | / _---=> hardirq/softirq
#                            || / _--=> preempt-depth
#                            ||| /     delay
#           TASK-PID   CPU#  ||||    TIMESTAMP  FUNCTION
#              | |       |   ||||       |         |
          <idle>-0     [019] d... 79056.554738: intel_idle <-cpuidle_enter_state
          <idle>-0     [019] d... 79056.555067: rcu_idle_exit <-cpuidle_enter_state
          <idle>-0     [019] d... 79056.555068: sched_idle_set_state <-cpuidle_enter_state
[root@nb282 tracing]#
```

filters

- simple syntax
  - it’s all implemented in the kernel
- function names, wildcards
  - exclude functions
- PID, children
  - function-fork option

filters

```
[root@nb282 ~]# cd /sys/kernel/tracing/
[root@nb282 tracing]# echo "vfs*" > set_ftrace_filter
[root@nb282 tracing]# echo "*read*" > set_ftrace_notrace
[root@nb282 tracing]# echo function > current_tracer
[root@nb282 tracing]# echo 1 > tracing_on
[root@nb282 tracing]# echo 0 > tracing_on
[root@nb282 tracing]# head -12 trace
# tracer: function
#
#                              _-----=> irqs-off
#                             / _----=> need-resched
#                            | / _---=> hardirq/softirq
#                            || / _--=> preempt-depth
#                            ||| /     delay
#           TASK-PID   CPU#  ||||    TIMESTAMP  FUNCTION
#              | |       |   ||||       |         |
            bash-103536 [002] .... 331803.181662: vfs_write <-ksys_write
            bash-103536 [002] .... 331803.181832: vfs_write <-ksys_write
 gnome-terminal--10149 [006] .... 331803.181985: vfs_write <-ksys_write
[root@nb282 tracing]#
```

demo

- terminal emulator (rxvt), shell (bash)
- press a key
  - terminal receives the key
  - terminal sends a character to the shell
    - character device
    - line discipline
    - hardware interface (pseudo tty)
- use ftrace to see what happens under the hood

demo
function tracer, filtering

trace-cmd (I)

- cmdline frontend for ftrace
  - uses tracefs internally
- packaged everywhere
- most important command: trace-cmd reset
- trace-cmd start, stop, show
- trace-cmd record, report
  - kernelshark GUI

trace-cmd (II)

```
[root@nb282 ~]# trace-cmd start -p function -l "vfs*" -n "*read*"
  plugin 'function'
[root@nb282 ~]# trace-cmd stop
[root@nb282 ~]# trace-cmd show | head -12
# tracer: function
#
#                              _-----=> irqs-off
#                             / _----=> need-resched
#                            | / _---=> hardirq/softirq
#                            || / _--=> preempt-depth
#                            ||| /     delay
#           TASK-PID   CPU#  ||||    TIMESTAMP  FUNCTION
#              | |       |   ||||       |         |
            bash-5383  [004] .... 114185.914828: vfs_write <-ksys_write
            bash-5383  [004] .... 114185.914930: vfs_statx <-__do_sys_newstat
 gnome-terminal--5077  [012] .... 114185.915264: vfs_write <-ksys_write
[root@nb282 ~]#
```

function graph tracer

- intercept start and end of each traced function
- graph structure of function calls
- track the time spent in a function

function graph tracer (II)

```
[root@nb282 ~]# trace-cmd start -p function_graph
  plugin 'function_graph'
[root@nb282 ~]# trace-cmd stop ; trace-cmd show
  ...
  1)               |            hrtimer_update_next_event() {
  1)               |              __hrtimer_get_next_event() {
  1)   0.071 us    |                __hrtimer_next_event_base();
  1)   0.635 us    |              }
  1)               |              __hrtimer_get_next_event()
                                  ...
  1)   2.386 us    |            }
[root@nb282 ~]#
```

demo
trace-cmd, function graph

events

- predefined static events that can be traced
- /sys/kernel/tracing/events/
  - each subdirectory is a group of related events

```
[root@nb282 ~]# cd /sys/kernel/tracing/
[root@nb282 tracing]# ls events/workqueue/
enable  workqueue_activate_work/  workqueue_execute_start/
filter  workqueue_execute_end/    workqueue_queue_work/
[root@nb282 tracing]# ls events/workqueue/workqueue_queue_work/
enable  filter  format  hist  id  trigger
[root@nb282 tracing]#
```

events (II)

```
[root@nb282 ~]# cd /sys/kernel/tracing/
[root@nb282 tracing]# cat events/workqueue/workqueue_queue_work/format
name: workqueue_queue_work
ID: 266
format:
        field:unsigned short common_type;       offset:0;       size:2; signed:0;
        field:unsigned char common_flags;       offset:2;       size:1; signed:0;
        field:unsigned char common_preempt_count;       offset:3;       size:1; signed:0;
        field:int common_pid;   offset:4;       size:4; signed:1;

        field:void * work;      offset:8;       size:8; signed:0;
        field:void * function;  offset:16;      size:8; signed:0;
        field:void * workqueue; offset:24;      size:8; signed:0;
        field:unsigned int req_cpu;     offset:32;      size:4; signed:0;
        field:unsigned int cpu; offset:36;      size:4; signed:0;

print fmt: "work struct=%p function=%ps workqueue=%p req_cpu=%u cpu=%u", REC->work, REC->f
unction, REC->workqueue, REC->req_cpu, REC->cpu
[root@nb282 tracing]#
```

events (III)

- the data fields can be used for filtering
- trigger : action when a filter matches
  - e.g. enable function tracing, show a stacktrace

events (IV)

```
[root@nb282 ~]# cd /sys/kernel/tracing/
[root@nb282 tracing]# trace-cmd list -e mmc
mmc:mmc_request_start
mmc:mmc_request_done
[root@nb282 tracing]# trace-cmd list -e mmc:mmc_request_done -F
system: mmc
name: mmc_request_done
ID: 2676
format:
        ...
        field:int cmd_err;      offset:12;      size:4; signed:1;
        ...
[root@nb282 tracing]# trace-cmd start -e mmc:mmc_request_done -f "cmd_err != 0"
[root@nb282 tracing]#
```

event demo

bug analysis with ftrace

```
[martin.kaiser@nb282 ~]$ grep test /*/*/*
bash: /usr/bin/grep: Argument list too long
[martin.kaiser@nb282 ~]$
```

- who is at fault?
  - grep? bash? libc? kernel?
- what's going wrong?

bug analysis demo

Thank you for your attention.

Freedigitalphotos/Master Isolated Images

function graph tracer : filters

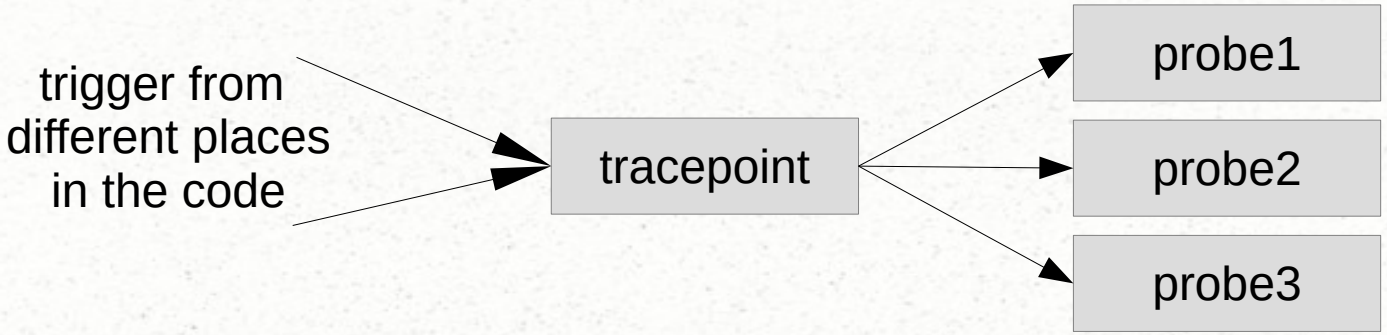
- two different filters
  - list the function?
  - start function graph?

	/sys/kernel/tracing/	trace-cmd start	action
function, enable	set_ftrace_filter	-l <func>	list the function no graph
graph, enable	set_graph_function	-g <func>	start graph tracing
disable	set_ftrace_notrace set_graph_notrace	-n <func>	disable tracing

tracepoints

- abstract concept that is the basis for events
- tracepoint == name, data fields
- probe function(s)
  - can be provided at runtime (modules, BPF)
- trigger the tracepoint -> probe(s) are called

tracepoints (II)



- event
  - tracepoint + probe that logs into the ringbuffer
- software that uses tracepoints, probes
  - e.g. Sysdig, SentinelOne, perf

perf

- one of the most prominent users of ftrace
- a performance analyzing tool
  - bundled with the linux kernel
  - actively developed
- interface to function (graph) tracers
  - uses tracefs

perf

- perf events
  - hardware performance counters
  - software events
  - ...
  - tracepoint events
    - they use the tracepoints from ftrace
    - with perf-specific probe functions

perf

```
[root@nb282 ~]# perf ftrace -G "kmem*" --graph-opts noirqs sleep 0.1
# tracer: function_graph
#
# CPU  DURATION                  FUNCTION CALLS
# |     |   |                     |   |   |   |
  4)               |  kmem_cache_free() {
  4)               |    obj_cgroup_uncharge() {
  4)   0.147 us    |      refill_obj_stock();
  4)   1.051 us    |    }
  4)   0.191 us    |    mod_objcg_state();
  4)   3.613 us    |  }
  ...
[root@nb282 ~]#
```

perf

```
[root@nb282 ~]# perf list

  bus-cycles                                         [Hardware event]
  cache-misses                                       [Hardware event]
  ...
  context-switches OR cs                             [Software event]
  page-faults OR faults                              [Software event]
  ...
  mmc:mmc_request_done                               [Tracepoint event]
  mmc:mmc_request_start                              [Tracepoint event]
  ...
[root@nb282 ~]#
```

perf

```
[root@nb282 ~]# perf stat -e "timer:hrtimer*" -e cs -e page-faults sleep 0.1

 Performance counter stats for 'sleep 0.1':

                1      timer:hrtimer_init
                3      timer:hrtimer_start
                2      timer:hrtimer_expire_entry
                2      timer:hrtimer_expire_exit
                2      timer:hrtimer_cancel
                1      cs
               57      page-faults

       0.102325429 seconds time elapsed
       ...
[root@nb282 ~]#
```

ftrace implementation

```
[root@nb282 ~]# trace-cmd start -p function ...
[root@nb282 ~]# trace-cmd show
        bash-10331 [009] .... 59876.278765: vfs_write <-ksys_write
```

intercept function calls

```
ssize_t vfs_write(struct file *file, ...)
{
    if (tracing_enabled_for_this_function)
       write_log_entry();

    ... do our work
}
```

- additional check in each function that can be traced
- condition is almost always false (tracing is off)

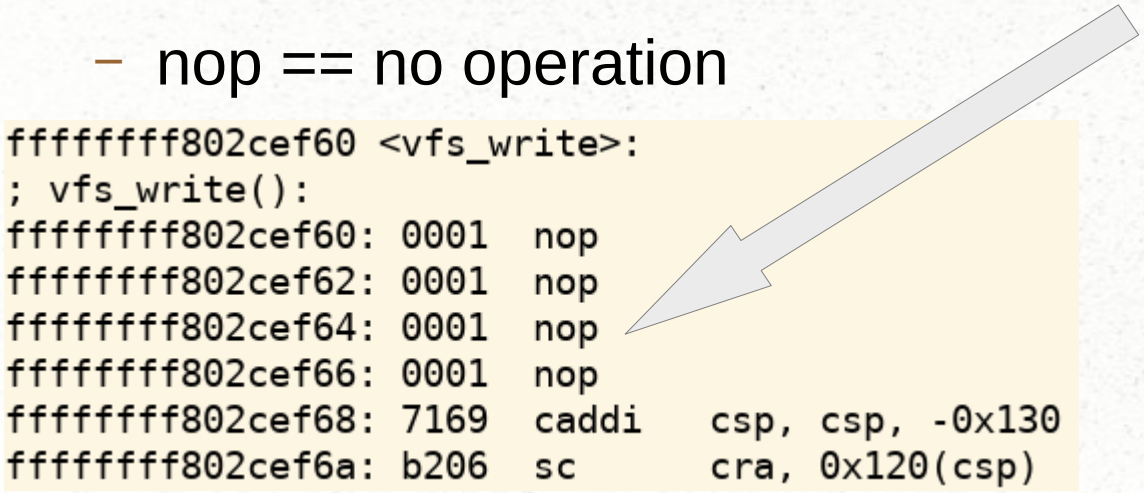
-> this approach is too slow

ftrace implementation (II)

- on/off switch: “tracing on for this function?”
  - checked very often -> must be fast
  - hardly ever changed -> can be slow
- patch the code at runtime
  - depends on compiler, architecture

ftrace implementation (III)

- make the compiler generate “empty code” at the start
  - nop == no operation



```
ffffffff802cef60 <vfs_write>:
; vfs_write():
ffffffff802cef60: 0001  nop
ffffffff802cef62: 0001  nop
ffffffff802cef64: 0001  nop
ffffffff802cef66: 0001  nop
ffffffff802cef68: 7169  caddi   csp, csp, -0x130
ffffffff802cef6a: b206  sc      cra, 0x120(csp)
```

- tracing off : keep the 4 x nop
- tracing on : replace 4 x nop with jump to log function

demo: function tracer, filtering

```
[root@nb282 tracing]# echo nop > current_tracer
[root@nb282 tracing]# echo "" > set_ftrace_filter
[root@nb282 tracing]# echo "" > set_ftrace_pid
[root@nb282 tracing]# echo 0 > tracing_on
[root@nb282 tracing]# echo > trace
```

```
[martin.kaiser@nb282 ~]$ echo $$
115763
[martin.kaiser@nb282 ~]$ pstree -s -p $$
systemd(1)───...───rxvt(115762)───bash(115763)───pstree(115834)
```

```
[root@nb282 tracing]# echo "*write*" > set_ftrace_filter
[root@nb282 tracing]# echo 115762 > set_ftrace_pid
[root@nb282 tracing]# echo function > current_tracer
[root@nb282 tracing]# echo 1 > tracing_on
[root@nb282 tracing]# cat trace_pipe
```

```
[martin.kaiser@nb282 ~]$ e
```

demo: function tracer, filtering (II)

```
rxvt-115762 [008] .... 73198.438343: __x64_sys_write <-do_syscall_64
rxvt-115762 [008] .... 73198.438361: ksys_write <-do_syscall_64
rxvt-115762 [008] .... 73198.438362: vfs_write <-ksys_write
rxvt-115762 [008] .... 73198.438382: __vfs_write <-vfs_write
rxvt-115762 [008] .... 73198.438383: tty_write <-vfs_write
rxvt-115762 [008] .... 73198.438386: tty_write_lock <-tty_write
rxvt-115762 [008] .... 73198.438388: n_tty_write <-tty_write
rxvt-115762 [008] .... 73198.438391: pty_write <-n_tty_write
rxvt-115762 [008] .... 73198.438400: tty_write_unlock <-tty_write
rxvt-115762 [008] .... 73198.439042: tty_write_room <-n_tty_poll
rxvt-115762 [008] .... 73198.439058: pty_write_room <-n_tty_poll
rxvt-115762 [008] .... 73198.439136: tty_write_room <-n_tty_poll
rxvt-115762 [008] .... 73198.439141: pty_write_room <-n_tty_poll
```

demo: trace-cmd, function graph tracer

```
root@nb282 tracing]# trace-cmd reset ; trace-cmd start \
                     -p function -P 115762 -l "*write*"
  plugin 'function'
[root@nb282 tracing]# cat trace_pipe
```

```
[martin.kaiser@nb282 ~]$ e
```

```
    ...
    rxvt-115762 [014] .... 73524.534909: pty_write_room <-n_tty_poll
    rxvt-115762 [014] .... 73524.552243: __x64_sys_writev <-do_syscall_64
    rxvt-115762 [014] .... 73524.552252: do_writev <-do_syscall_64
    rxvt-115762 [014] .... 73524.552252: vfs_writev <-do_writev
    ...
^C
[root@nb282 tracing]# trace-cmd stop
[root@nb282 tracing]#
```

demo: trace-cmd, function graph tracer (II)

```
[root@nb282 tracing]# trace-cmd reset
[root@nb282 tracing]# trace-cmd start -p function_graph -P 115762 \
       -g __x64_sys_write --max-graph-depth 10 \
       -n smp_irq_work_interrupt -n kprobe_ftrace_handler
  plugin 'function_graph'
[root@nb282 tracing]# cat trace_pipe
```

```
[martin.kaiser@nb282 ~]$ e
```

```
  8)       |  __x64_sys_write() {
 ...
  8)       |              pty_write() {
  8)       |                tty_insert_flip_string_and_push_buffer() {
...
  8)       |                  tty_insert_flip_string_fixed_flag.part.9() {
...
  8)       |                  queue_work_on() {
  8)  4.876 us  |                    __queue_work();
  8)  5.963 us  |                  }
...
```

event demo

```
[root@nb282 tracing]# trace-cmd reset
[root@nb282 tracing]# trace-cmd start -p function_graph \
   -P 12223 -g pty_write --max-graph-depth 5 \
   -n "*mutex*" -n "*spin_lock*" -n smp_irq_work_interrupt \
   -O nofuncgraph-duration -e workqueue
  plugin 'function_graph'
[root@nb282 tracing]# cat trace_pipe
```

```
[martin.kaiser@nb282 ~]$ e
```

```
  8) pty_write() {
 ...
  8)     queue_work_on() {
  8)       __queue_work() {
  8)         /* workqueue_queue_work: work struct=000000009b958723
function=flush_to_ldisc workqueue=0000000098641a65 req_cpu=8192
cpu=4294967295 */
  8)         /* workqueue_activate_work: work struct 000000009b958723 */
  8)       }
```

bug analysis demo

This command fails

```
martin@reykholt:~$ grep test /*/*/*
-bash: /usr/bin/grep: Argument list too long
```

See if we can use strace to get a first idea.

```
martin@reykholt:~$ strace -f grep test /*/*/*
-bash: /usr/bin/grep: Argument list too long
```

(user shell has pid 3630)

```
root@reykholt:~# strace -f -p 3630
```

```
martin@reykholt:~$ grep test /*/*/*
```

```
[pid  3765] execve("/usr/bin/grep", ["grep", "test",
"/bin/X11/[", ...], 0x557042ee8130 /* 28 vars */) = -1 E2BIG (Argument
list too long)
```

bug analysis demo

or use ftrace to see failing syscalls from children

```
root@reykholt:~# trace-cmd start -P 3630 -c \
    -e raw_syscalls:sys_exit -f "common_pid != 3630 && ret < 0"
root@reykholt:~# cat /sys/kernel/tracing/trace_pipe

                                        martin@reykholt:~$ grep test /*/*/*

    <...>-3943    [003] .....  2757.394452: sys_exit: NR 59 = -7
     ...
```

the execve syscall fails -> try to figure out what happens internally
look for functions related to execve where we could start tracing

```
root@reykholt:~# trace-cmd list -f execve
do_execveat_common.isra.0
kernel_execve
__x64_sys_execve
...
```

bug analysis demo

- watch events for entering and exiting execeve* syscalls
  - enable tracing on entry, disable tracing on exit
- create a call tree for do_execveat_common.isra.0
  - filter out irrelevant functions that are called frequently

```
root@reykholt:~# trace-cmd reset
root@reykholt:~# trace-cmd start -p function_graph -P 3630 -c \
  -e syscalls:sys_enter_execve* -R traceon \
  -e syscalls:sys_exit_execve*  -R traceoff \
  -g do_execveat_common.isra.0 --max-graph-depth 3 \
  -O funcgraph-tail -O nofuncgraph-duration -O nofuncgraph-cpu \
  -n handle_mm_fault -n __cond_resched -n mm_alloc \
  -n mmput -n vm_area_alloc -n insert_vm_struct
```

```
martin@reykholt:~$ grep test /*/*/*
```

bug analysis demo

```
root@reykholt:~# cat /sys/kernel/tracing/trace_pipe

/* sys_execve(filename: 557042f5a6f0, argv: ..., envp: ...) */
do_execveat_common.isra.0() {
  alloc_bprm() {
    do_open_execat();
    ...
  } /* alloc_bprm */
  ...
  bprm_stack_limits();
  free_bprm() {
    ...
  } /* free_bprm */
  putname() {
    kmem_cache_free();
  } /* putname */
} /* do_execveat_common.isra.0 */
/* sys_execve -> 0xfffffffffffffff9 */
```

- would be helpful to see return values
  - funcgraph-retval option
  - CONFIG_FUNCTION_GRAPH_RETVAL
  - or define an fprobe
- sequence
  - alloc_...
  - bprm_stack_limits
  - free_...
    -> bprm_stack_limits fails

bug analysis demo

- bprm_stack_limits function
  - small, mostly comments
  - "Limit to 1/4 of the max stack size ... for the argv+env strings."

```
martin@reykholt:~$ ulimit -a
...
stack size   (kbytes, -s) 512

martin@reykholt:~$ martin@reykholt:~$ grep test /*/*/*
-bash: /usr/bin/grep: Argument list too long
```

bug analysis demo

open a new shell -> the default stack size is 8K

```
martin@reykholt:~$ ulimit -s
8192
martin@reykholt:~$ grep test /*/*/*
... lots of output, no error
```