Tracing Tools

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whoami

- Senior Software Engineer
- RHEL systemd maintainer
- SW engineer interested in tracing and debugging

Motivation

Have you ever wanted to answer questions like,

- What files in `/etc` are being accessed on the system ?
- How big are memory allocations done by [DAEMON] (insert you favorite) ?
- What process is a source of slow filesystem operations (e.g. slower than 50 ms) ?

Agenda

- PART I – Introduction
  - Tracing vs. Debugging
  - Goals
  - Methodology
- PART II – Tools
  - strace and ltrace (ptrace)
  - trace-cmd (ftrace)
  - SystemTap (kprobes)
  - bcc-tools (eBPF)
- PART III – Exercises

PART I – Introduction

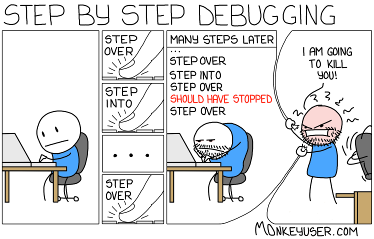
Intro – Debugging vs. Tracing

Debugging

The process of identifying and removing errors from computer software.

Approaches

- Staring into the code
- Debug logging
- Debuggers
  - `gdb`
  - `lldb`



Intro – Debugging vs. Tracing

Tracing

Non-intrusive observation and monitoring of a software system.

Approaches

- Syscall monitoring
- Gathering execution traces
- Stack sampling
- Debug logging

Intro – Goals

Goals

- Better understanding of the system behavior
- Tracing should be as non-intrusive as possible
- In-kernel summarization (if possible) and statistical data gathering

Right tool for the job

What tracing tools should I use?

Unfortunately, answer to this question on Linux is not straight forward. We need to understand at least two things,

- Goal
- Tracing target

Goal	Target	Tool
Good observability	kernel	`SystemTap`
Versatility	user-space/kernel	`SystemTap`
Non-intrussivness	kernel	`trace-cmd`[1]
In-kernel data aggregation	kernel	`bpftrace`
Ease of Use	user-space	`strace`

[1] depends on the filter setting

PART II – Tools

ptrace()

API

```
long ptrace(enum __ptrace_request request, pid_t pid, void
*addr, void *data);
```

- Both strace and ltrace leverage ptrace() subsystem
- Very old syscall and clunky interface
- ptrace first appeared in Version 6 of AT&T UNIX
- ptrace allows you to dynamically attach to the process to observe and control its execution
-
    - **request** – type of requested action
    - **pid** – TID of a target process
    - **addr** – User-space address where to write or read from
    - **data** – Data buffer (exact type depends on request type)
- **tracer** – process which calls ptrace()
- **tracee** – process whose TID is specified as the second argument to ptrace()

ptrace() - Requests

- **PTRACE_ATTACH** – Attaches tracer to a target[2]
- **PTRACE_DETACH** – Detach tracer from a target
- **PTRACE_SYSCALL** – Resume execution of a target until next syscall enter/exit
- **PTRACE_GETREGS** – Fetches general purpose registers of a target
- **PTRACE_SETREGS** – Sets content of a general purpose registers of a target
- **PTRACE_PEEKTEXT** – Read a word of program text[3] of a target from `addr`
- **PTRACE_POKETEXT** – Write a word at `*addr` to a target address-space

[2] Only one tracer per target

[3] Linux doesn't have code and data address spaces

ptrace() - Demo

- DEMO

Tools - strace

Properties

- `strace` is a well known system call tracer
- Leverages `ptrace()` subsystem
- Target is stopped at every system call twice (entry, exit)
- Tracing is slow
- Very intrusive and not suitable for diagnosing production issues
- Limited visibility (syscall layer only)
- Very good reporting
- System call tampering (delay, fault injection)

Example: `strace ls -l 2>&1 | head -n5`

```
execve("/usr/bin/ls", ["ls", "-l"], 0x7ffe0914fff8 /* 34 vars */) = 0
brk(NULL)                               = 0x564d3e45b000
arch_prctl(0x3001 /* ARCH_??? */, 0x7ffd875de7e0) = -1 EINVAL
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
```

Tools - strace

Interesting features

- `strace -e trace=%file` – trace filesystem related syscalls
- `strace -e trace='/(l|f)stat'` – trace lstat or fstat
- `strace -k` – stack trace at each syscall
- `strace -y` – print files associated with fd
- `strace -yy` – print network protocols associated with fd
- `strace -C` – system call statistics
- `strace -s 512` – make sure we have buffer big enough to print string arguments into
- `strace -P <path>` – print syscall accessing the path
- `strace -e trace='/open(at)?' -P /var -e inject=all:error=ENOENT ls -l /var` – fail open or openat for of /var

Tools - ltrace

- Library call tracer
- Tool similar in nature to strace
- Adds breakpoint at PLT trampoline to notify ltrace about library call
- Very slow
- Not suitable for use in production
- Upstream is now unmaintained

Example: ltrace -e opendir+readdir ls -l /tmp/foo

```
ls->opendir("/tmp/foo")       = { 3 }
ls->readdir({ 3 })            = { 1976910, "bar" }
ls->readdir({ 3 })            = { 1966081, ".." }
ls->readdir({ 3 })            = { 1975851, "." }
ls->readdir({ 3 })            = { 1980802, "baz" }
ls->readdir({ 3 })            = nil
total 0
-rw-rw-r--. 1 msekleta msekleta 0 Jan 25 10:03 bar
-rw-rw-r--. 1 msekleta msekleta 0 Jan 25 10:03 baz
+++ exited (status 0) +++
```

Tools - ltrace

ltrace oneliners

```
# count number of memory allocations done by libselinux
ltrace -c -e 'malloc@libselinux.so.1' matchpathcon /etc/fstab >/dev/null

# show usage count for sd_bus APIs
ltrace -c -e 'sd_bus*@libsystemd*' systemctl status cups >/dev/null
```

Tools - trace-cmd

- Interacts with Ftrace tracer that is built-in to the kernel
- In order to configure Ftrace tracer it writes files in `/sys/kernel/debug/tracing`.
- Directory contains mount of tracefs filesystem (or `trace-cmd` will mount it for you)
- Ftrace supports both static (predefined trace points) and dynamic (function tracing) tracing
- Ftrace fundamentally works in two phases
  - Collection phase (per-CPU buffers in which selected event traces are recorded)
  - Post-processing phase (content of tracing buffers is concatenated and stored in trace.dat file)

Tools - trace-cmd-record

trace-cmd oneliners

```
# trace writes bigger than 10k bytes
trace-cmd record -e syscalls:sys_enter_write -f 'count > 10000'

# record function graph of all kernel function called by echo
trace-cmd record -p function_graph -F /bin/echo foo

# list all networking related events
trace-cmd list -e 'net:.*'

# trace all ext4 related events
trace-cmd record -e ext4 ls
```

kProbes

- Linux framework for in-kernel dynamic tracing
- Allows to break into any kernel function
- Specified handlers are run once the breakpoint is hit
- 2 probe types
  - kprobes
  - kretprobes
- kprobes replace first byte at designated address with breakpoint instruction (int3 on x86_64)
- After breakpoint is hit execution state is saved and "pre-handler" is called
- kprobes then single step the trapped instruction
- kprobes then call "post-handler"
- Execution continue with next instruction

kProbes - example

- DEMO

Tools - SystemTap

- Complete framework for Linux tracing
- `dnf install -y systemtap && stap-prep`
- SystemTap takes tracing script, translates it to C which gets compiled into kernel module
- Previous point is a major problem for production use cases (partially solved by compilation server)
- kprobes and uprobes, i.e. with SystemTap you can trace both kernel and user-space
- Language is C-like and relatively easy to learn

Tools - SystemTap - Language

```
global odds, evens

probe begin {
  for (i = 0; i < 10; i++) {
    if (i % 2)
      odds [no++] = i
    else
      evens [ne++] = i
  }
  delete odds[2]
  delete evens[3]
  exit()
}

probe end {
  foreach (x+ in odds)
    printf ("odds[%d] = %d", x, odds[x])
  foreach (x in evens-)
    printf ("evens[%d] = %d", x, evens[x])
}
```

Tools - SystemTap - Probe points

Probe points

kernel.function(PATTERN) kernel.function(PATTERN).call
kernel.function(PATTERN).return
module(MPATTERN).function(PATTERN).call
module(MPATTERN).function(PATTERN).return
process("PATH").function("NAME")
process("PATH").statement("*@FILE.c:123")
process("PATH").library("PATH").function("NAME")
process("PATH").library("PATH").statement("*@FILE.c:123")

- Probe point context variables,
- `stap -L 'kernel.function("_do_fork")'`
- Tapset – big library of "ready-made" systemtap scripts

Tools - SystemTap - What to print?

- **tid()** – The id of the current thread.
- **pid()** – The process (task group) id of the current thread. uid() The id of the current user.
- **execname()** – The name of the current process. cpu() The current cpu number.
- **gettimeofday_s()** – Number of seconds since epoch. get_cycles() Snapshot of hardware cycle counter.
- **pp()** – A string describing the probe point being currently handled.
- **ppfunc()** – If known, the the function name in which this probe was placed.
- **$$vars** – If available, a pretty-printed listing of all local variables in scope.
- **print_backtrace()** – If possible, print a kernel backtrace.
- **print_ubacktrace()** – If possible, print a user-space backtrace.

Berkley Packet Filter (BPF)

- Berkley Packet Filter (BPF) is a technology used for packet filtering in UNIX like operating systems
- First introduced in the seminal paper by Steve McCanne and Van Jacobson in 1992
- The BSD Packet Filter: A New Architecture for User-level Packet Capture
- Example:

```
# tcpdump -i eno1 -d ip
(000) ldh      [12]
(001) jeq      #0x800          jt 2    jf 3
(002) ret      #262144
(003) ret      #0
```

BPF concepts

- BPF is a special assembly-like language which is specifically tailored for packet filtering
- Notice special addressing mode on previous slide ([12] is an offset to L2 PDU)
- Filter expression is compiled (usually using `libpcap`) into the BPF program which is then loaded to the kernel

  ```
  setsockopt(s, SOL_SOCKET, SO_ATTACH_FILTER, prog, sp)
  ```
- Kernel contains virtual machine (VM) able to interpret BPF byte code on every received packet

Extended Berkley Packet Filter (eBPF)

- eBPF is Linux only (so far) extension of classic BPF (cBPF)
- Instruction set is much richer
- Virtual Machine has now 10, 64 bit registers (cBPF only had 2)
- In-kernel JIT compiler
- Possibility to hook into various kernel subsystems
  - probe points
  - kprobes
  - cgroups
  - sockets
  - packet forwarding
  - system calls
- Subsystem is manipulated by `bpf` syscall (`man 2 bpf`)
- Possibility to share data structures (e.g. arrays, hash-maps) with kernel
- In-kernel aggregations (useful for histograms and stack-trace counting)

Extended Berkley Packet Filter (eBPF)

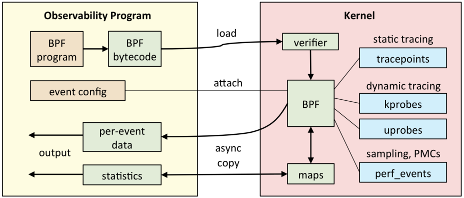
bpf system call

```
int bpf(int cmd, union bpf_attr *attr, unsigned int size);
```

- **cmd** – Requested action (e.g. `BPF_PROG_LOAD`, `BPF_MAP_CREATE`, `BPF_MAP_ELEM_LOOKUP`)
- **attr** – Precise value stored in `attr` union depends on action
- **size** – Size of object pointed by `attr`

Extended Berkley Packet Filter (eBPF) - Verifier

- Before BPF program is loaded the kernel will run static analyzer (verifier) to determine if it is safe to load it
- Verifcation consists of:
  - Checking for loops
  - Depth-first-search (DFS) of program's Control Flow Graph (loops, unreachable instruction analysis)
  - Program run simulation
  - Checks for accesses or jumps based on unintialized data
  - Checks for out-of-bound accesses
  - Checks for pointer arithmetics (in Secure Mode, i.e. processes w/o `CAP_SYS_ADMIN`)



BCC - Installation

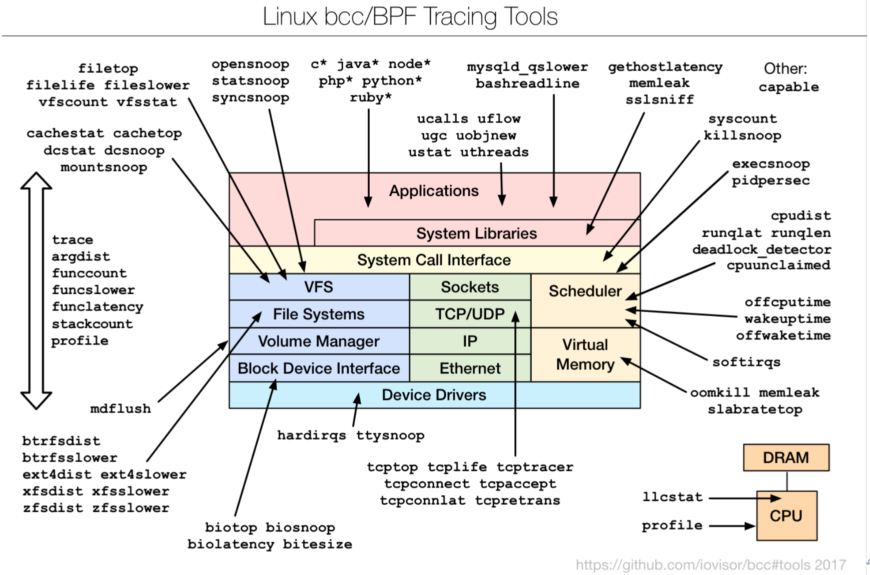
- Option 1 – Install tools on your workstation
  - `# dnf -y install bcc-tools kernel-devel-$(uname -r)`
  - `# export PATH=/usr/share/bcc/tools/:$PATH`
- Option 2 – Try the tools in virtual machine (Vagrantfile)

```
$ cat Vagrantfile
Vagrant.configure("2") do |config|
  config.vm.box = "fedora/28-cloud-base"

  config.vm.provider "libvirt" do |lv|
    lv.memory = "1024"
    lv.cpus = "2"
  end

  config.vm.provision "shell", inline: <<-SHELL
     sudo dnf -y install bcc-tools kernel-devel-$(uname -r)
     sudo echo 'export PATH=/usr/share/bcc/tools:$PATH' >> /root/.bashrc
  SHELL
end
```

BCC - Overview



BCC - Tools

- `execsnoop` - trace `execve()` syscalls
- `opensnoop` - trace `open()` syscalls
- `mountsnoop` - trace `mount()` syscalls
- `statsnoop` - trace `stat()` syscalls
- `ext4slower` - trace ext4 operations slower than threshold (10ms by default)
- `gethostlatency` - trace latency of DNS resolution
- `tcpaccept`, `tcpconnect` - TCP related tracing tools
- `runqlen`, `runqlat` - scheduler related tracing tools
- `filetop` - identify "hot files" on the system

BCC - Tracing

- ```
  # Count all malloc() calls done by PID 1
  funccount -p 1 c:malloc
  ```
- ```
  # Collect and count all stack traces leading tcp_sendmsg()
  stackcount tcp_sendmsg
  ```
- ```
  # Count the libc write() calls for PID 1 by file descriptor
  argdist -p 181 -C 'p:c:write(int fd):int:fd'
  ```
- ```
  # Trace all malloc calls and print the size of the requested allocation
  trace ':c:malloc "size = \%d", arg1'
  ```
- ```
  # List all tracepoints
  tplist
  ```
- ```
  # List information about tracepoint cgroup:cgroup_attach_task
  tplist -v cgroup:cgroup_attach_task
  ```
- ```
  # Trace cgroup migrations system wide
  trace 't:cgroup:cgroup_attach_task "\%d", args->pid'
  ```
  ```

PART III – Excercises

Excercises

- Print all getsockopt() and setsockopt() syscalls done by systemctl on AF_UNIX sockets
- What is the ratio of successful to failed socket option calls for systemctl ?
- What files systemd opens (PID1) during restart of cups.service?
- Is there a memory leak in cups server during the dispatch of scheduler status request (lpstat -r)?
- Can you trace one process with strace and ltrace at the same time?
- What is the ICMP packet size sent by ping with default settings?

Excercises

- How many calls to kmalloc() is triggered by send+recv of single ICMP packet?
- How many allocation requests are bigger than 64 bytes?
- How many times does systemd call unit_load() on cups restart? In addition, print user-space backtrace on each call.
- What is protocol overhead of HTTP download of google.com (curl www.google.com)?
- What tool would you use in order to trace IPC via signals?

References

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