L41: Kernels and Tracing

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15 October 2015

Reminder: last time

1. What is an operating system?
2. Systems research
3. About the module
4. Lab reports

This time: Tracing the kernel

1. DTrace
2. The probe effect
3. The kernel: Just a C program?
4. A little on kernel dynamics: How work happens

Dynamic tracing with DTrace

- Bryan M. Cantrill, Michael W. Shapiro, and Adam H. Leventhal. *Dynamic Instrumentation of Production Systems*, USENIX Annual Technical Conference, USENIX, 2004.
  - “Facility for dynamic instrumentation of production systems”
  - Unified and safe instrumentation of kernel and userspace
  - Zero *probe effect* when not enabled
  - Dozens of ‘providers’ representing different trace sources
  - Tens (hundreds?) of thousands of instrumentation points
  - C-like high-level control language with predicates and actions
  - User-defined variables, thread-local variables, associative arrays
  - Data aggregation and speculative tracing
- Adopted in Solaris, Mac OS X, and FreeBSD; module for Linux
- Heavy influence on Linux SystemTap
- **Our tool of choice for this module**

DTrace scripts

- Human-facing C-like language
- One or more {*probe name*, *predicate*, *action*} tuples
- Expression limited to control side effects (e.g., no loops)
- Specified on command line or via a `.d` file

```
fbt::malloc:entry /execname == "csh"/ { trace(arg0); }
```

probe name Identifies the probe(s) to instrument; wildcards allowed; identifies the *provider* and a provider-specific *probe name*

predicate Filters cases where action will execute

action Describes tracing operations

D Intermediate Format (DIF)

```
root@beaglebone:/data # dtrace -Sn
  'fbt::malloc:entry /execname == "csh"/ { trace(arg0); }'
```

```
DIFO 0x0x8047d2320 returns D type (integer) (size 4)
OFF OPCODE      INSTRUCTION
00: 29011801    ldgs DT_VAR(280), %r1 ! DT_VAR(280) = "execname"
01: 26000102    sets DT_STRING[1], %r2 ! "csh"
02: 27010200    scmp %r1, %r2
03: 12000006    be   6
04: 0e000001    mov  %r0, %r1
05: 11000007    ba   7
06: 25000001    setx DT_INTEGER[0], %r1 ! 0x1
07: 23000001    ret  %r1

NAME             ID   KND SCP FLAG TYPE
execname         118  scl glb r    string (unknown) by ref (size 256)


DIFO 0x0x8047d2390 returns D type (integer) (size 8)
OFF OPCODE      INSTRUCTION
00: 29010601    ldgs DT_VAR(262), %r1 ! DT_VAR(262) = "arg0"
01: 23000001    ret  %r1

NAME             ID   KND SCP FLAG TYPE
arg0             106  scl glb r    D type (integer) (size 8)
```

Some kernel DTrace providers in FreeBSD

Provider	Description
`callout_execute`	Timer-driven callouts
`dtmalloc`	Kernel `malloc()`/`free()`
`dtrace`	DTrace script events (`BEGIN`, `END`)
`fbt`	Function Boundary Tracing
`io`	Block I/O
`ip`, `udp`, `tcp`, `sctp`	TCP/IP
`lockstat`	Locking
`proc`, `sched`	Kernel process/scheduling
`profile`	Profiling timers
`syscall`	System call entry/return
`vfs`	Virtual filesystem

- Providers represent data sources – types of instrumentation
- Apparent duplication: FBT vs. event-class providers?
  - Efficiency, expressivity, interface stability, portability

Tracing kernel `malloc()` calls

- Trace first argument to kernel `malloc()` for `csh`
- Note: captures both successful and failed allocations

```
root@beaglebone:/data # dtrace -n
  'fbt::malloc:entry /execname=="csh"/ { trace(arg0); }'
```

Probe Use FBT to instrument `malloc()` prologue

Predicate Limit actions to processes executing `csh`

Action Trace the first argument (`arg0`)

```
CPU     ID                    FUNCTION:NAME
  0   8408                     malloc:entry          64
  0   8408                     malloc:entry        2748
  0   8408                     malloc:entry          48
  0   8408                     malloc:entry         392
^C
```

Aggregations

- Often we want summaries of events, not detailed traces
- DTrace allows early, efficient *reduction* using aggregations

Aggregation	Description
`count()`	Number of times called
`sum()`	Sum of arguments
`avg()`	Average of arguments
`min()`	Minimum of arguments
`max()`	Maximum of arguments
`stddev()`	Standard deviation ofnts
`lquantize()`	Linear frequency distribution (histogram)
`quantize()`	Log frequency distribution (histogram)

- Scalable multicore implementations (i.e., commutative)
- `@variable = function();printa()` to print

Profiling kernel `malloc()` calls by `csh`

```
root@beaglebone:/data # dtrace -n 'fbt::malloc:entry
  /execname=="csh"/ { @traces[stack()] = count(); }'
```

Probe Use FBT to instrument `malloc()` prologue

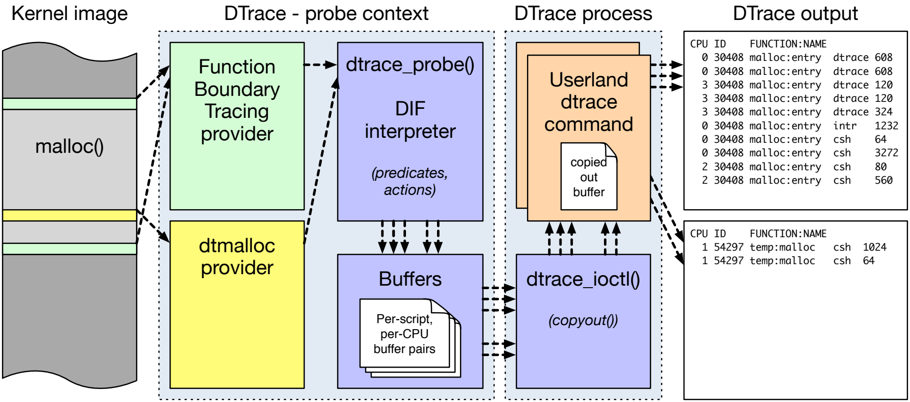
Predicate Limit actions to processes executing `csh`

Action Keys of associative array are stack traces (`stack()`); values are aggregated counters (`count()`)

```
^C
              kernel`malloc
              kernel`fork1+0x14b4
              kernel`sys_vfork+0x2c
              kernel`swi_handler+0x6a8
              kernel`swi_exit
              kernel`swi_exit
                3
...
```

DTrace: implementation

```
dtrace -n 'fbt::malloc:entry { trace(execname); trace(arg0); }'
```




```
dtrace -n 'dtmalloc::temp:malloc /execname="csh"/ { trace(execname); trace(arg3); }'
```

The ‘probe effect’

- The *probe effect* is the unintended alteration in system behaviour that arises from measurement
- Why? Software instrumentation is *active*: execution is changed
- DTrace minimises *probe effect* when not being used...
  - ... but has a very significant impact when it is
  - Disproportionate effect on probed events
- Potential perturbations:
  - Execution speed relative to other cores (e.g., lock hold times)
  - Execution speed relative to external events (e.g., timer ticks)
  - Microarchitectural effects (e.g., cache footprint, branch predictor)
- What does this mean for us?
  - Don’t benchmark while running DTrace ...
  - ... unless benchmarking DTrace
  - Be aware that traced application may behave differently
  - E.g., more timer ticks will fire, I/O will “seem faster”

Probe effect example: `dd` execution time

- Simple (naive) microbenchmark
- `dd(1)` copies blocks from an input to an output
- Copy one 10M buffer from `/dev/zero` to `/dev/null`
- Execution time measured with `/usr/bin/time`

```
# dd if=/dev/zero of=/dev/null bs=10m count=1 status=none
```

- Simultaneously, run various DTrace scripts
- Compare resulting execution times using `ministat`

Probe effect example 1: Memory allocation

- Using the `dtmalloc` provider, count kernel memory allocations

```
dtmalloc::: { @count = count(); }
```

```
% ministat no-dtrace dtmalloc-count
x no-dtrace
+ dtmalloc-count
+------------------------------------------------------------------------------+
|                                        *                                     |
|                                        *                                     |
|                                        *                                    +|
|x                                       *                                    +|
|x                                       *                                    +|
|*                                       *                                    *|
|        |_______________|______A______M__________A_____|___________________|  |
+------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  11           0.2          0.22          0.21    0.20818182  0.0060302269
+  11           0.2          0.22          0.21    0.21272727  0.0064666979
No difference proven at 95.0% confidence
```

- No statistically significant overhead at 95% confidence level

Probe effect example 2: Locking operations

- `lockstat` provider tracks lock acquire, release, ...
- 6 calls to `malloc`, but 170K locking operations!

```
lockstat::: { @count = count(); }
```

```
ministat no-dtrace lockstat-count
x no-dtrace
+ lockstat-count
+------------------------------------------------------------------------------+
|   x                                                                       +|
|   x                                                                       +|
|   x                                                                   +   +|
|x  x                                                                   +   +|
|x  x                                                                   +   +|
|x  x  x                                                             +  +   +|
| |_A_|                                                                 |_A_M|
+------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  11           0.2          0.22          0.21    0.20818182  0.0060302269
+  11          0.42          0.44          0.44    0.43454545  0.0068755165
Difference at 95.0% confidence
0.226364 +/- 0.00575196
108.734% +/- 2.76295%
(Student's t, pooled s = 0.0064667)
```

- 109% overhead to count all `lockstat` probes!

Probe effect example 2: Limiting to `dd`?

- Limit `action` to processes with name `dd`

```
lockstat::: /execname == "dd"/ { @count = count(); }
```

```
ministat no-dtrace lockstat-count-dd
x no-dtrace
+ lockstat-count-dd
+--------------------------------------------------------------------------------+
|                                                                          +   |
|  x                                                                       +   |
|  x                                                                       +   |
|  x                                                                       +   |
|  x                                                                       +   |
|x x                                                                       +   |
|x x                                                                       +   |
|x x x                                                                 + + + +|
||_A|                                                                   |_A|  |
+--------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  11           0.2          0.22          0.21    0.20818182  0.0060302269
+  11          0.54          0.57          0.56    0.55818182  0.0075075719
Difference at 95.0% confidence
0.35 +/- 0.0060565
168.122% +/- 2.90924%
(Student's t, pooled s = 0.00680908)
```

- Well, crumbs. Now the overhead is 168%!

Probe effect example 3: Locking stack traces

- Gather more information in `action`: capture call stacks

```
lockstat::: { @stacks[stack()] = count(); }
lockstat::: /execname == "dd"/ { @stacks[stack()] =
  count(); }
```

```
ministat no-dtrace lockstat-stack*
x no-dtrace
+ lockstat-stack
* lockstat-stack-dd
+--------------------------------------------------------------------------------+
|                                                                          *     |
|                                                                          *     |
|                                                                          *     |
|                                                                          *     |
|xx                                                                   ++   **   |
|xx                                                                   ++   **   |
|xx                                                                +  +++ ** *+|
|AM                                                                  |_MA_|A|   |
+--------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  11           0.2          0.22          0.21    0.20818182  0.0060302269
+  11          1.38          1.57          1.44     1.4618182   0.058449668
1.25364 +/- 0.0369572
602.183% +/- 17.7524%
*  11           1.5          1.55          1.51     1.5127273   0.014206273
1.30455 +/- 0.00970671
626.638% +/- 4.66261%
```

The kernel: "Just a C program"?

I claimed that the kernel was mostly "just a C program".
This is mostly true, especially if you look at high-level subsystems.

Userspace	**Kernel**
`crt/csu`	`locore`
`rtld`	Kernel linker
Shared objects	Kernel modules
`main()`	`main()`, `platform_start`
`libc`	`libkern`
POSIX threads API	`kthread` KPI
POSIX filesystem API	VFS KPI
POSIX socket API	`socket` KPI
DTrace	DTrace
...	...

The kernel: not just *any* C program

- Core kernel: ≈3.4M LoC in ≈6,450 files
  - Kernel foundation: Built-in linker, object model, scheduler, memory allocator, threading, debugger, tracing, I/O routines, timekeeping
  - Base kernel: VM, process model, IPC, VFS w/20+, filesystems, network stack (IPv4/IPv6, 802.11, ATM, ...), crypto framework
  - Includes roughly ≈70K lines of assembly over ≈6 architectures
- Alternative C runtime – e.g., `SYSINIT`, `curthread`
- Highly concurrent – really, very, very concurrent
- Virtual memory makes pointers .. odd
- Debugging features such as `WITNESS` lock order verifier
- Device drivers: ≈3.0M LoC in ≈3,500 files
  - ≈415 device drivers (may support multiple devices)

Spelunking the kernel

```
/usr/src/sys> ls
Makefile        ddb/            mips/           nfs/            sys/
amd64/          dev/            modules/        nfsclient/      teken/
arm/            fs/             net/            nfsserver/      tools/
boot/           gdb/            net80211/       nlm/            ufs/
bsm/            geom/           netgraph/       ofed/           vm/
cam/            gnu/            netinet/        opencrypto/     x86/
cddl/           i386/           netinet6/       pc98/           xdr/
compat/         isa/            netipsec/       powerpc/        xen/
conf/           kern/           netnatm/        rpc/
contrib/        kgssapi/        netpfil/        security/
crypto/         libkern/        netsmb/         sparc64/

/usr/src/sys> ls kern
Make.tags.inc           kern_racct.c            subr_prof.c
Makefile                kern_rangelock.c        subr_rman.c
bus_if.m                kern_rctl.c             subr_rtc.c
capabilities.conf       kern_resource.c         subr_sbuf.c
clock_if.m              kern_rmlock.c           subr_scanf.c
...
```

- Kernel source lives in `/usr/src/sys`:
  `kern/` - core kernel features
  `sys/` - core kernel headers
- Useful resource: `http://fxr.watson.org/`

How work happens in the kernel

- Kernel code executes concurrently in multiple threads
  - User threads in kernel (e.g., system call)
  - Shared worker threads (e.g., callouts)
  - Subsystem worker threads (e.g., network-stack worker)
  - Interrupt threads (e.g., clock ticks)
  - Idle threads

```
root@beaglebone:/data # procstat -at
  PID    TID COMM             TDNAME           CPU  PRI STATE   WCHAN
    0 100000 kernel           swapper           -1   84 sleep   swapin
    0 100006 kernel           dtrace_taskq      -1   84 sleep   -
...
   10 100002 idle             -                 -1  255 run     -
   11 100003 intr             swi3: vm           0   36 wait    -
   11 100004 intr             swi4: clock (0)   -1   40 wait    -
   11 100005 intr             swi1: netisr 0    -1   28 wait    -
...
   11 100018 intr             intr16: ti_adc0    0   20 wait    -
   11 100019 intr             intr91: ti_wdt0    0   20 wait    -
   11 100020 intr             swi0: uart        -1   24 wait    -
...
  739 100064 login            -                 -1  108 sleep   wait
  740 100079 csh              -                 -1  140 sleep   ttyin
  751 100089 procstat         -                  0  140 run     -
```

Work processing and distribution

- Many operations begin with system calls in a user thread
- But they may trigger work in many other threads; for example:
  - Triggering a callback in an interrupt thread when I/O is complete
  - Eventual write back of data to disk from the cache
  - Delayed transmission if TCP isn't able to send
- We will need to care about these things, as not all the work we are analysing will be in the user thread performing a system call.
- Several major subsystems provide this:

callout	Closure called after wall-clock delay
eventhandler	Closure called for key global events
task	Closure called eventually
SYSINIT	Function called when module loads/unloads

- (Where closure in C means: function pointer, opaque data pointer)

For next time

- Read Ellard and Seltzer, *NFS Tricks and Benchmarking Traps*
- Skim handout, *L41: DTrace Quick Start*
- Be prepared to try out DTrace on a real system