Kernels and Tracing

Lecture 2, Part 1: DTrace

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Kernels and tracing

- DTrace
- The **probe effect**
- Kernel dynamics

Lecture 2, Part 1

Lecture 2, Part 2

Lecture 2, Part 3

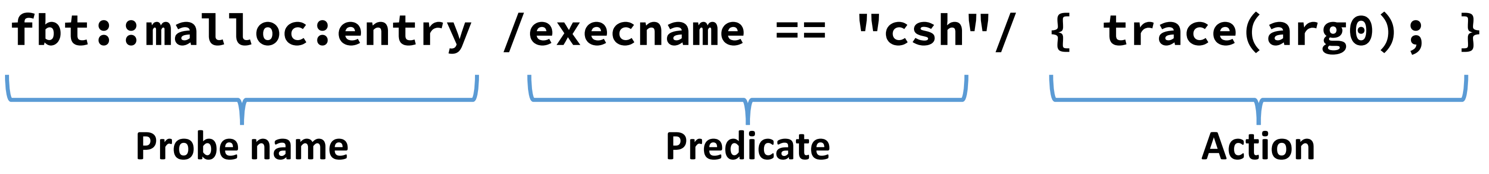
Dynamic tracing with DTrace

- Bryan M. Cantrill, Michael W. Shapiro, and Adam H. Leventhal. *Dynamic Instrumentation of Production Systems*, USENIX ATC 2004.
  - "Facility for dynamic instrumentation of production systems"
  - Unified and safe **instrumentation** of kernel and user space
  - Zero **probe effect** when not enabled
  - Dozens of **providers** representing different trace mechanisms
  - Tens (hundreds?) of thousands of **instrumentation probes**
  - **D language**: C-like scripting language with **predicates**, **actions**
  - Scalar variables, thread-local variables, associative arrays
  - **Data aggregation** and **speculative tracing**
- First-class feature in: Solaris, Mac OS X, FreeBSD, Windows; third-party Linux module
- Wide influence – e.g., on Linux SystemTap, eBPF
- **Our tool of choice in this course**

DTrace scripts

- Human-facing, C-like **D Programming 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

Probe name	Identifies the probe(s) to instrument; wildcards allowed; identifies the provider and provider-specific probe name
Predicate	Filters cases where action will execute
Action	Describes tracing operations



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

Some FreeBSD DTrace providers

- Providers represent data sources – instrumentation types:

Provider	Description
callout_execute	Timer-driven “callout” event probes
dtmalloc	Kernel `malloc()/free()`
dtrace	DTrace script events (`BEGIN`, `END`)
fbt	Function Boundary Tracing (function prologues, epilogues)
io	Block I/O read/write
ip,udp,tcp,sctp	TCP/IP events
lockstat	Kernel locking primitives
proc,sched	Kernel process, scheduling primitives
profile	Profiling timers
syscall	System-call entry/return
vfs	Virtual File System operations

- Apparent duplication: FBT vs. event-class providers?
  - Efficiency, expressivity, interface stability, portability

Tracing kernel malloc() calls

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

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

Probe	Use FBT to instrument `malloc()` function 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 – summarising traces

- **Aggregations** allow early, efficient reduction
  - Scalable multicore implementations (i.e., commutative)

```
@variable = function(.. args ..);
printa(@variable)
```

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 of arguments
`lquantize()`	Linear frequency distribution (histogram)
`quantize()`	Log frequency distribution (histogram)

Profiling kernel malloc() calls by csh

```
fbt::malloc:entry
/execname=="csh"/
{ @traces[stack()] = count(); }
```

Probe	Use FBT to instrument `malloc()` function 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
...
```

D Intermediate Format (DIF)

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

Predicate

```
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)
```

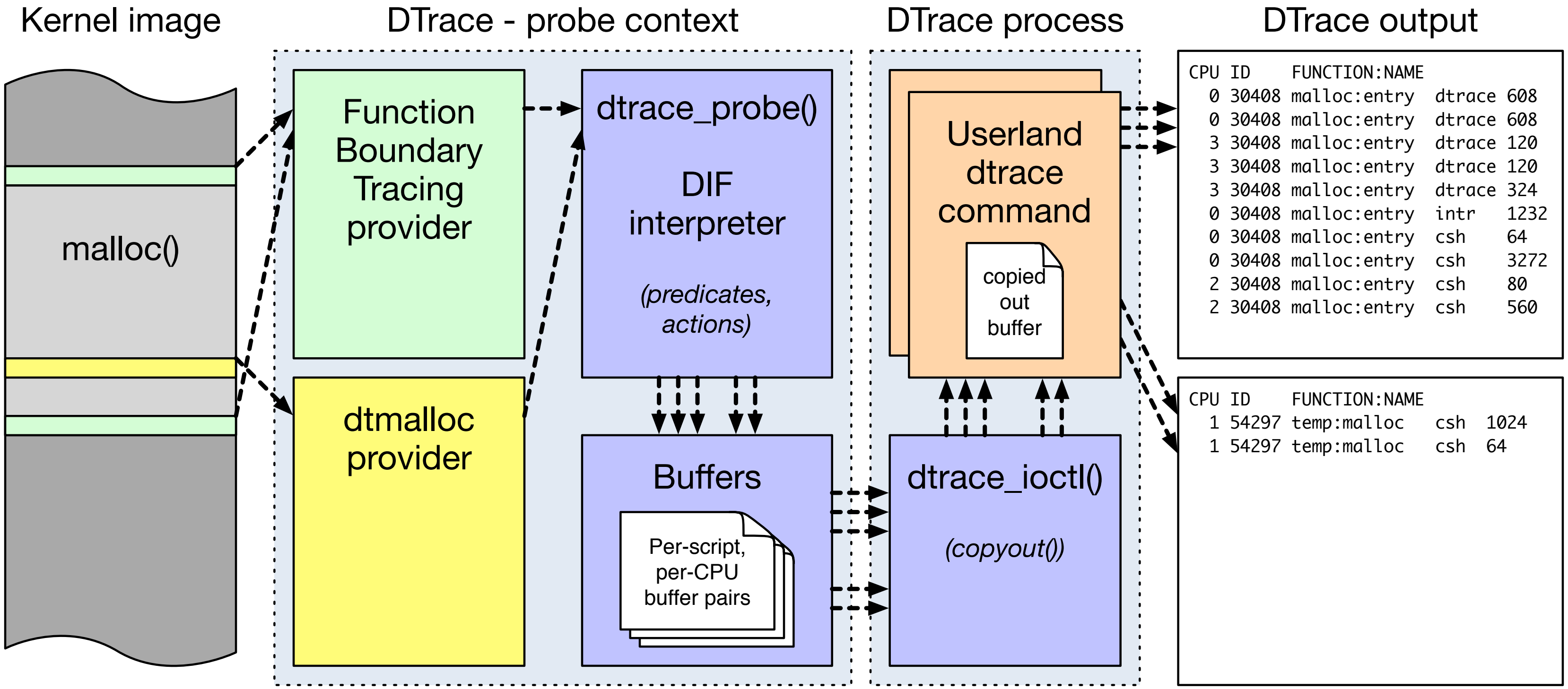
Action

```
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)
```

DTrace: Implementation

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



```
CPU ID     FUNCTION:NAME
  0 30408 malloc:entry  dtrace 608
  0 30408 malloc:entry  dtrace 608
  3 30408 malloc:entry  dtrace 120
  3 30408 malloc:entry  dtrace 120
  3 30408 malloc:entry  dtrace 324
  0 30408 malloc:entry  intr   1232
  0 30408 malloc:entry  csh    64
  0 30408 malloc:entry  csh    3272
  2 30408 malloc:entry  csh    80
  2 30408 malloc:entry  csh    560
```

```
CPU ID     FUNCTION:NAME
  1 54297 temp:malloc   csh  1024
  1 54297 temp:malloc   csh  64
```

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