DTrace: Dynamic Tracing For Solaris

Bryan Cantrill (bmc@eng)

Mike Shapiro (mws@eng)

Solaris Kernel Technologies

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Bryan Cantrill (bc30992@japan)

Mike Shapiro (ms36066@sfbay)

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ITOPS APPROVED

A Modern Tracing Framework

- Must have zero probe effect when disabled
- Must allow for novel tracing technologies
- Must allow for thousands of probes
- Must allow arbitrary numbers of consumers
- Unwanted data must be pruned as early as possible in the data chain
- Data must be coalesced whenever possible, and as early as possible

The DTrace Vision

- Build a tracing framework that provides concise answers to arbitrary questions
- Enable quantum leap in performance analysis and engineering
- Improve RAS through continuous tracing
- Accelerate project development
- Eliminate DEBUG and other special kernels: *all* facilities available in production

IBM MVS Tracing

- MVS provided wealth of tracing facilities, notably GTF and CTRACE
- IPCS console provided commands to enable, filter, and display GTF, CTRACE trace records
- Extensive probes provided for base operating system, channel programs
- GTRACE() assembler macro used to record data in a user program; can later be merged

GTF Example

- Operator console:

```
START GTF.EXAMPLE1
AHL103I TRACE OPTIONS SELECTED--SYSM,USR,DSP
00 AHL125A RESPECIFY TRACE OPTIONS OR REPLY U
REPLY 00,U
AHL031I GTF INITIALIZATION COMPLETE
```

- IPCS GTFTRACE output:

```
DSP ASCB 00F44680 CPU 001      PSW 070C1000
                  TCB 00AF2370 R15 80AF2858
                  R0  00000001 R1  FDC9E5D4

    GMT-07/02/89 00:29:08.155169
```

GTF Example

- Operator console:

```
START GTF.EXAMPLE1
AHL103I TRACE OPTIONS SELECTED--SYSM,USR,DSP
00 AHL125A RESPECIFY TRACE OPTIONS OR REPLY U
              F IN             ION COMPLETE

DSP ASCB 00F44680 CPU 001       PSW 070C1000
                  TCB 00AF2370 R15 80AF2858
                  R0  00000001 R1  FDC9E5D4

    GMT-07/02/89 00:29:08.
```

dispatch event on CPU1

address space control block

processor status word

task control block

saved register values

VTRACE

- Kernel tracing framework developed early in Solaris 2 (1991)
- Provided a C macro to designate a probe site; some probe effect even when disabled
- Additionally, applications could issue fast trap to record events in in-kernel buffer
- In-kernel buffers could be continuously read out and streamed to disk

VTRACE, cont.

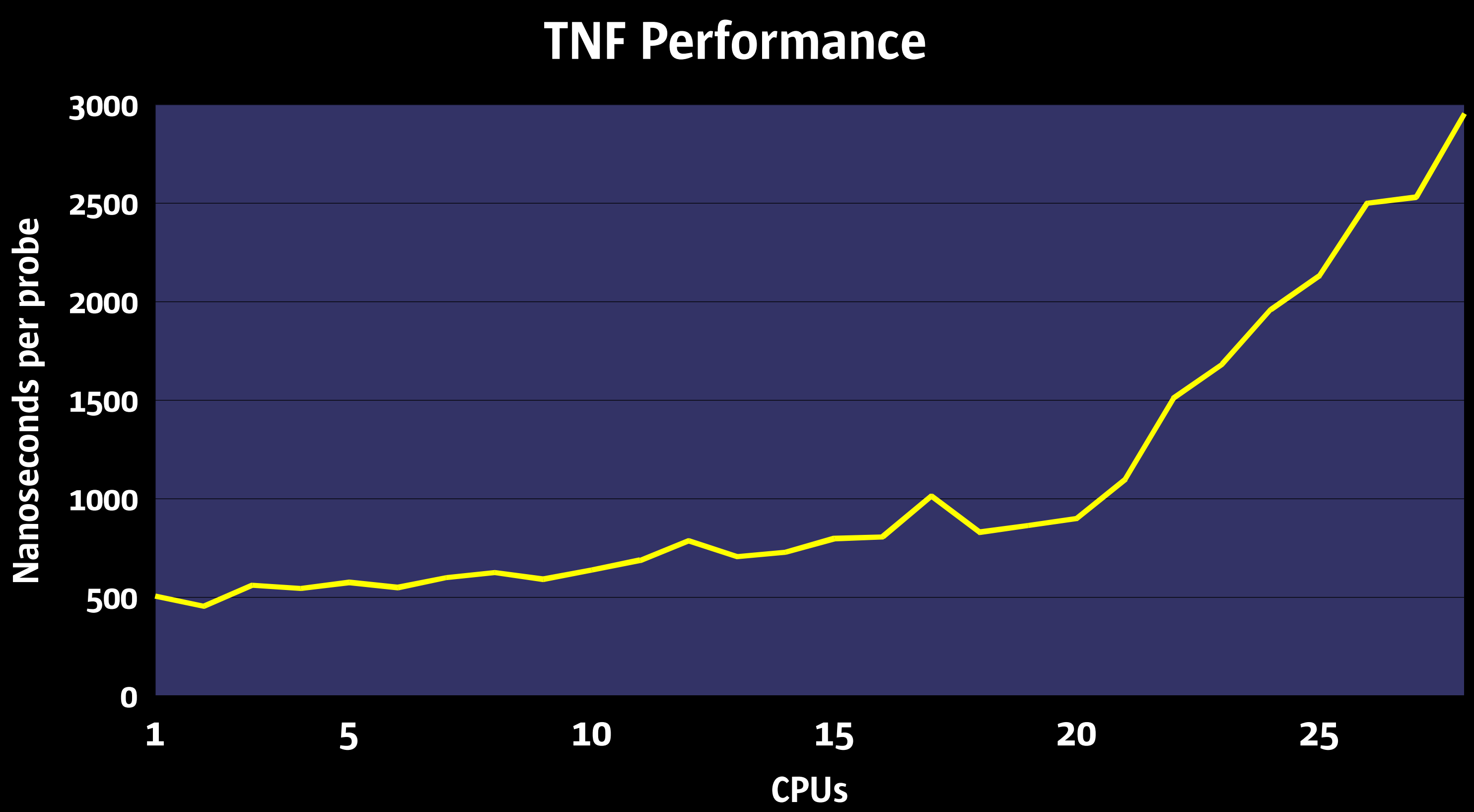
- Scalable and lightweight when enabled
- Fair coverage: ≈1,000 trace points
- Used to solve real performance problems
- As a result of disabled probe effect, required a special kernel
- Fell into disrepair during 64-bit port

TNF

- *Trace Normal Form* tracing framework introduced in Solaris 2.5
- Originally a user-level framework (LSARC 1993/650); kernel support tacked on (PSARC 1994/165)
- Like VTRACE, provides C macro to designate a probe site; induces load, compare and branch even if disabled

TNF, cont.

- Uses pseudo per-CPU buffering, resulting in suboptimal CPU scaling



TNF, cont.

- Some of TNF's failings:
  - Too few probes (≈30 probes in common kernel code)
  - Crude filtering (only based on process ID, and even then doesn't work for scheduling events)
  - No control over data generated by each probe
  - Doesn't allow for continuous collection of data
  - Doesn't correlate kernel data to application activity
  - Bizarre data format designed for use only in postmortem analysis

KernInst

- Kernel instrumentation tool developed at Wisconsin [Tamches, Miller, et al.]
- User-level daemon performs run-time register analysis of kernel object code
- Code patches, trampoline code, and instrumentation are inserted using driver
- Overcomplicated by living outside of core OS
- Does not provide sufficient predicate support
- Unsafe probe insertion causes OS failure!

Linux DProbes

- Dynamic instrumentation kit for Linux kernel [Moore, IBM LTC, et al.]
- Replaces kernel text with breakpoint trap that vectors to user RPN probe program
- Also provides access to Intel debug registers
- Currently under active development
- DProbes facility not part of stock kernel
- Significant safety issues (more later ...)

Competitive Landscape

Feature	GTF	vtrace	TNF	KInst	DProbe	Notes
user/kernel/merged	M	M	M	K	K	users want combined timeline of user and kernel events
probe coverage	●	◒	✗	◒	◒	framework must provide sufficient probes to solve most problems
disabled probe effect	○	✗	○	●	●	ideal framework has zero probe effect when disabled
scalability	○	●	○	○	○	concurrent probe firings must scale to arbitrary number of CPUs
safety	●	●	◒	✗	✗	no way for user to induce fatal machine or OS failure
extensibility	◒	○	○	◒	◒	framework should allow easy addition of probes and providers
data filtering	●	✗	✗	○	●	users should be able to filter on arbitrary conditions at probe site
arbitrary recording	✗	✗	✗	○	●	users should be able to record arbitrary data on probe firing
self describing	◒	○	◒	✗	✗	type information available to consumers for all recorded data
run-time analysis	●	✗	✗	●	◒	run-time analysis tools should be provided, not just post-mortem
stock availability	●	✗	●	◒	◒	tracing facilities must be available on production systems
stable abstractions	◒	◒	●	✗	✗	framework must provide stable abstractions for layered tools

Providers

- Tracing frameworks have historically been tied to a single tracing methodology
- Conversely, new tracing methodologies have had to invent their own frameworks
- In DTrace, the tracing framework is formally separated from tracing *providers*
- Allows for faster adoption of and provides significant leverage for novel tracing methodologies

Probes

- A trace point in DTrace is called a *probe*
- A probe is identified by a tuple consisting of Provider, Module, Function and Name
- Probes may have Module and Function unspecified (such probes are said to be *unanchored*)
- Each probe has a unique 32-bit ID

Predicates and Actions

- Idea: Provide flexible boolean expressions that can control tracing activities, e.g.

```
if (pid == process of interest)
     then trace data of interest
```

- Must allow completely arbitrary queries to be formulated by user or layered tool
- Must evaluate at probe firing time to prune data stream at earliest opportunity

Provider Interface

- Provider makes available all known probes
- Framework calls into provider to enable a specific probe
- Framework handles multiplexing of multiple consumers of a single probe
- Provider indicates that an enabled probe is hit by calling **`dtrace_probe`**(), specifying probe ID

`dtrace_probe()`

- **`dtrace_probe`**() is called to take appropriate actions (if any) when an enabled probe is hit
- Can be called from any context in which C may be called, e.g.:
  - From high-level interrupt context
  - While interrupts are disabled
  - In synchronization primitives (e.g. **`mutex_enter`**())
  - While dispatcher locks are held

dtrace_probe(), cont.

- Disables interrupts for its duration
  - Substantially simpler than implementing lock-free data structures
  - Prevents preemption, CPU migration
  - As fast as performing an atomic memory operation
  - Synchronous cross calls can be used to guarantee that no threads remain in critical section
- Converts probe ID to internal data structure for further processing

`dtrace_probe()`, cont.

- Iterates over a per-probe chain of *enabling control blocks* (ECBs)
- Each ECB corresponds to an *enabling* of a probe
- The ECB abstraction allows:
  - A given consumer to have multiple, different enablings of a single probe
  - Disjoint consumers to have disjoint enablings of a single probe

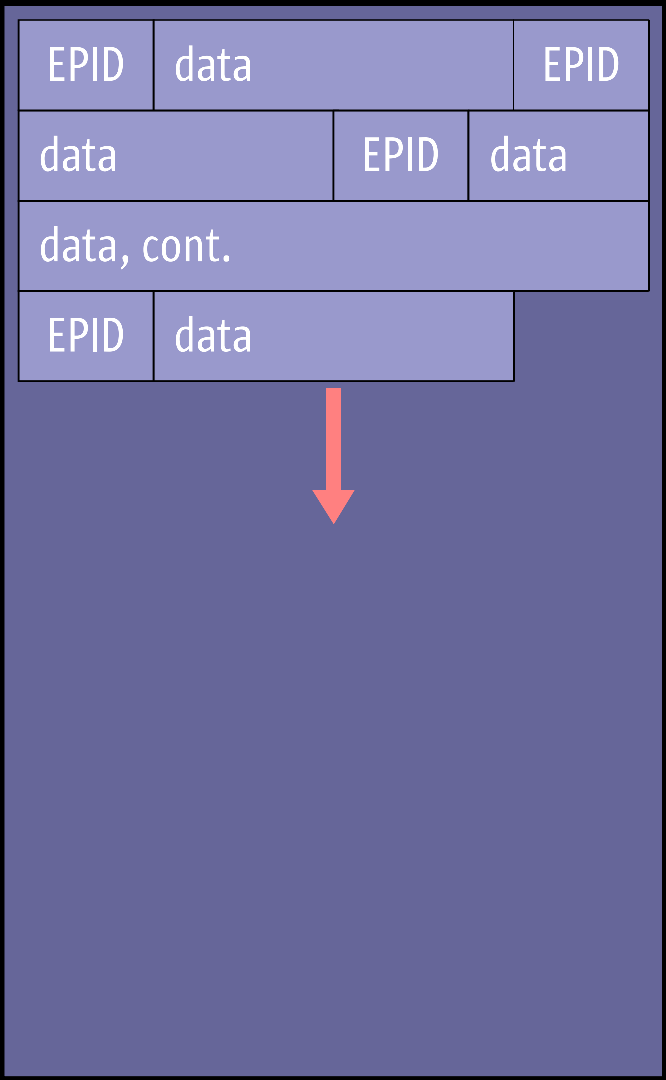
Enabling Control Blocks

- Each ECB contains:
  - An optional *predicate*
  - A list of one or more *actions*
  - A pointer to an array of per-CPU *buffers*
- Each ECB has a corresponding *enabled probe ID* (EPID)
- EPID space is per consumer

Enabling Control Blocks, cont.

- Actions are taken on an ECB if and only if:
  - There does not exist a predicate, or
  - The predicate evaluates to a non-zero value
- Actions may identify data to be stored into a *trace record*
- Actions need not generate trace data
  - May update variable state (more later)
  - May affect system state in a defined way (e.g. BREAKPOINT, PANIC)

Trace Records



- Record size is *constant* per ECB (and therefore per EPID)
- Records consist of 32-bit EPID, followed by some amount of data
- Library determines record size and layout using a separate EPID dictionary

Trace Records, cont.

- Library's EPID dictionary can be built dynamically: as a new EPID is seen in the data stream, the library queries for the corresponding record size and layout
- Separating the data stream from the metadata stream facilitates run-time analysis tools
- Lack of data/metadata separation is a serious deficiency in TNF

Buffers

- Buffers are per consumer, per CPU
- Buffers are always allocated in pairs: an *active* buffer and a *spare* buffer
- A buffer is consumed by:
  - Issuing a synchronous cross call to the corresponding CPU to *switch* active buffer with spare buffer
  - Copying out used portion of newly spare buffer (formerly the active buffer) to user-level

Buffer Management

- If buffer is full when a data-generating action is taken, a per-buffer *drop count* is incremented and no action is taken
- It is up to consumers to minimize drop counts by reading buffers sufficiently often
- Drop counts are copied out to user-level alongside buffer data; consumers always know if data is incomplete

Buffer Management, cont.

- A consumer may optionally indicate that a buffer is to be treated as a *ring buffer*
- Ring buffers wrap on overflow, writing over older data
- Consumers can avoid data loss by reading buffer sufficiently often
- Useful primarily to provide “black box” style event recording

Function Boundary Tracing

- Would like a probe before every function entry and after every function return
- Would like to implement probes by hot patching kernel text only when enabled -- thereby avoiding performance effect when disabled
- But how to hot patch text?

Branch Insertion?

- Idea is to patch probe point to be an annulled branch-always into a jump table
- Must perform static analysis to ascertain dead registers
- Analysis must somehow statically determine trap level; failure to do so can induce RED state exception
- e.g. KernInst

Software Trap Insertion?

- Idea is to patch desired code to be a trap-always instruction
- Must perform static analysis to avoid placing trap-always instruction where trap level can be non-zero
- Failure to do so can induce RED state exception
- e.g. Hot Diagnosis

Branch Insertion, revisited

- If we *only* patch a function's initial save instruction, we solve both of the problems with branch insertion:
  - Trap level is implicitly considered: code at TL > 0 may not arbitrarily issue a save
  - Register analysis is obviated by the save: immediately after the save, locals and outputs are dead

Entry Patching

Function

```
save  %sp, -0xc0, %sp
ldx   [%i0+ 0x3b0], %l6
...
```

We patch the save instruction to be an annulled branch-always into a per-probe entry in a per-module jump table

Entry Patching

Function

```
ba,a   . + offset
ldx    [%i0+ 0x3b0], %l6
...
```

Per module FBT table

```
...
save   %sp, -0xc0, %sp
set    probe_id, %o0
mov    %i0, %o1
...
sethi  %hi(pc - 4), %g1
call   dtrace_probe
or     %g1, %lo(pc - 4), %o7
...
```

The jump table entry:

- Performs the patched-over save
- Moves the inputs into the outputs
- Sets **%o7** to be (**patched_pc** - 4)
- Calls **dtrace_probe**()

Entry Patching, cont.

Function

```
sethi %hi(0x1494800),%g2
sethi %hi(0x140a000),%g1
save  %sp, -0xb0, %sp
ldx   [%g2 + 0x98], %g3
...
```

- The first instruction of a non-leaf function is not always a save instruction

- Correctly patching the save instruction in this case would require static register analysis: live registers volatile across the call to **`dtrace_probe`**() must be preserved

Entry Patching, cont.

- We instead patch the first instruction to be the annulled branch-always
- In this case, the jump table entry:
  - Performs a **`MINFRAME`** save
  - Moves the inputs into the outputs
  - Calls **`dtrace_probe`**()
  - Performs a restore
  - Branches back to (**`patched_pc`** + 4) with the patched-over instruction in the delay slot

Entry Patching, cont.

Function

```
ba,a  . + offset
sethi %hi(0x140a000),%g1
save  %sp, -0xb0, %sp
ldx   [%g2 + 0x98], %g3
...
```

Per module FBT table

```
...
save     %sp, -MINFRAME, %sp
set      probe_id, %o0
mov      %i0, %o1
...
call     dtrace_probe
mov      %i4, %o5
restore
ba       . + offset
sethi    %hi(0x1494800), %g2
...
```

Return Patching

Function

```
...
0x17c: mov     1, %i0
0x180: ret
0x184: restore
```

- ret/restore couplets can be patched in much the same way as save instructions
- The ret is patched to be an annulled branch-always into a jump table entry

Return Patching, cont.

Function

```
...
0x17c: mov      1, %i0
0x180: ba,a     . + offset
0x184: restore
```

Per module FBT table

```
...
set      probe_id, %o0
mov      0x180, %o1
call     dtrace_probe
mov      %i0, %o2
ret
restore
...
```

The jump table entry:

- Calls **dtrace_probe**(), passing both the return value and the offset of the ret
- On return from **dtrace_probe**(), performs the ret/restore couplet

Return Patching, cont.

Function

```
...
0x17c: stx     [%g2], %g3
0x180: call    mutex_exit
0x184: restore %g0,%l0,%o0
```

- ret/restore couplets are not the only way to return from a non-leaf routine
- call/restore and jmpl/restore couplets are used to implement tail-call elimination

Return Patching, cont.

Function

```
...
0x17c: stx      [%g2], %g3
0x180: ba,a     . + offset
0x184: restore %g0,%l0,%o0
```

Per module FBT table

```
...
set      probe_id, %o0
mov      0x180, %o1
call     dtrace_probe
mov      %i0, %o2
call     mutex_exit
restore %g0,%l0,%o0
...
```

Principle is the same:

- control-transfer instruction is patched to be an annulled branch-always
- Jump table entry performs control-transfer/restore couplet upon return from **`dtrace_probe`**()

Return Patching, cont.

Function

```
...
0x17c: ldx     [%g2], %g3
0x180: jmpl    %g3,%o7
0x184: restore %g0,%g2,%o0
```

- Both jmpl and restore can operate on register operands
- Must preserve operands volatile across the call to **`dtrace_probe`**() (i.e., inputs and globals)

Return Patching, cont.

Function

```
...
0x17c: ldx     [%g2], %g3
0x180: ba,a    . + offset
0x184: restore %g0,%g2,%o0
```

Per module FBT table

```
...
mov     %g3, %l1
mov     %g2, %l2
set     probe_id, %o0
mov     0x180, %o1
call    dtrace_probe
mov     %i0, %o2
jmpl    %l1, %o7
restore %g0,%l2,%o0
...
```

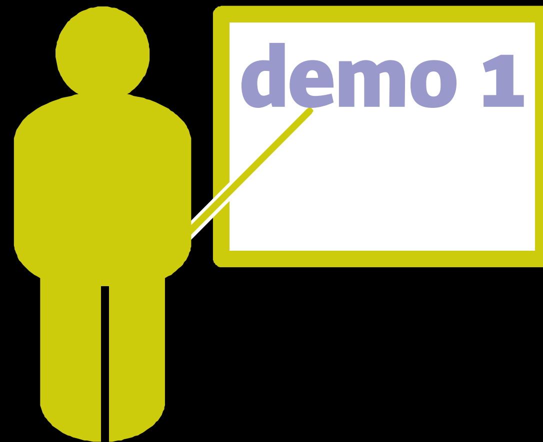
– The volatile registers are moved into unused locals

– The instructions using the volatile operands are restructured to be in terms of the local

Choosing Eligible Functions

- Always err on the side of caution: if a function looks like it's trying to be clever or appears otherwise strange, don't create probes for it
- Only create probes for functions containing both a patchable entry and a patchable return
- (Well, plus **`resume_from_zombie`**())

dtrace(1M) syntax



dtrace [-i *id*]

[-P *prov*]

[-m [*prov*:] *mod*]

[-f [[*prov*:] *mod*:] *func*]

[-n [[[*prov*:] *mod*:] *func*:] *name*]

Language Design

- The kernel is written in C, so the natural choice for low-level predicates is C:

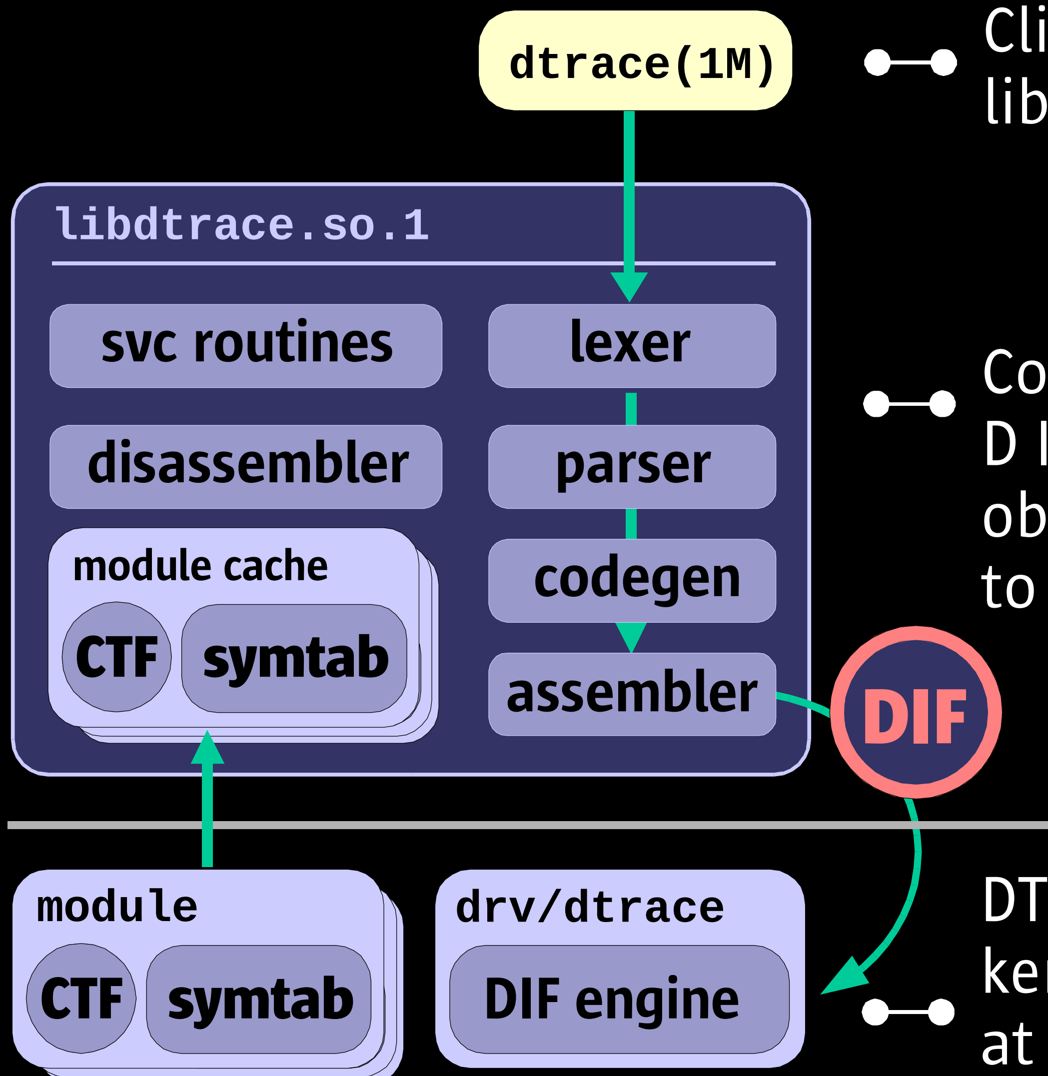
```
curthread->t_cpu->cpu_id == 0 &&
curthread->t_cpu->cpu_idle_thread ==
curthread ...
```

- The Kernel Stabs project (PSARC 2001/021) provided native type info in CTF, so it is possible to build a dynamic evaluator
- Same language for predicates and actions

Introducing "D"

- Complete access to native kernel C types
- Complete access to statics and globals
- Complete support for all ANSI-C operators
- Support for strings as a first-class citizen
- Support for built-in variables (timestamp, curthread, arguments, machine regs, etc.)
- Compiler provided as a library API

Implementing D



- Clients send D expressions to library for compilation
- Compiler stack produces D Intermediate Format (DIF) objects that can be bound to probe locations
- DTrace driver stores DIF in the kernel and executes program at probe firing time

DIF Architecture

- Small RISC architecture ideal for simple emulation or on-the-fly code generation
  - variable number of 64-bit registers (%r0 = 0)
  - 64-bit arithmetic and logical instructions
  - 1, 2, 4, and 8-byte safe memory loads
  - standard branches and condition codes
  - instructions to access variables, strings
  - ~50 opcodes, ~200 line emulator (plus some supporting routines for loads, variables, etc.)

DIF Example

- D expression: "**`curthread->t_cpu`**"
- DIF code:

```
ldgs 256, %r1   ! 256 = "curthread"
setx 0x00000000.000000a8, %r2
add  %r1, %r2, %r1
ldx  [%r1], %r1
ret  %r1
```

- DIF object: DIF
  - text section
  - string table
  - variable table
  - return type

DIF Safety

- All DIF objects are validated by the kernel:
  - valid opcodes
  - valid registers
  - valid string refs
  - valid variables
  - reserved bits must be zero
- Only **forward** branches are permitted
- Limit on maximum size of DIF object
- DTrace runtime handles invalid loads, misaligned loads, and division by zero
- DTrace runtime prevents access to i/o space addresses using new vmem arena

DIF Load Safety

- DIF engine load routines check alignment and i/o space arena before issuing load
- Per-CPU DTrace fault protection flag is set
- If `hment` search fails and protection is on, sfmmu sets fault flag and issues **done** instead of calling `sfmmu_pagefault`()
- Failed load aborts processing of current ECB

D Strings

- First-class strings provided to avoid ambiguity of **`char*`** and **`char[]`** in C
- Quoted strings are assigned string type
- Scalars can be promoted to string type using new **`stringof()`** operator
- Operators <, <=, >, >=, !=, == overloaded as strcmp(**3C**); promote **`char*`** and **`char[]`**:

```
curthread->t_procp->p_user.u_comm == "ksh"
```

D Limitations

- Still need to find some solution for #defines that are used as flag bits:

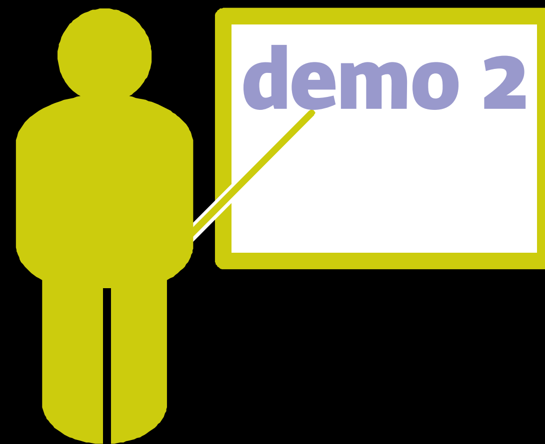
  `(curthread->t_proc_flag & TP_PRVSTOP)`

- Preprocessor approach possible but messy
- Ideally extend compiler or tools and CTF to support association directly in C source
- Solution would also benefit other debugging tools (e.g. mdb(**1**) **`::print`**)

Linux DProbes Comparison

- RPN-like IR developed in advance of forthcoming high-level language
- Safety issues not thoroughly considered:
  - user can induce panic if probes are placed improperly
  - user can modify registers, memory, write to i/o ports
  - validation performed in tool and libraries, not kernel
  - infinite loop problem handled by forcing user to specify **`jmp_max=123`** in probe program

dtrace(1M) syntax

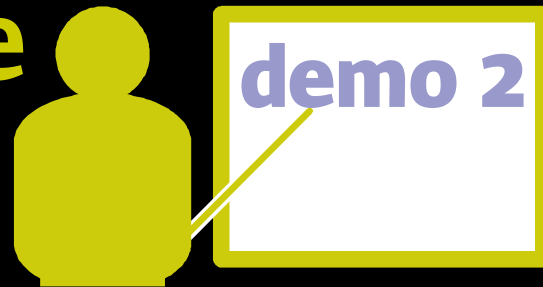


dtrace [-i *id* [*predact*]]
  [-P *prov* [*predact*]]
  [-m [*prov*:] *mod* [*predact*]]
  [-f [[*prov*:] *mod*:] *func* [*predact*]]
  [-n [[[*prov*:] *mod*:] *func*:] *name* [*predact*]]

predact ⇒ [/ *predicate* /] { *action* }

Sun microsystems

dtrace(1M) example




```
# dtrace -n ´write32:entry
  / curthread->t_procp->p_user->u_comm == "ksh" /
  { trace(curthread->t_procp->p_pidp->pid_id) }´
dtrace: ’write32:entry’ matched 1 probe.
CPU     ID    FUNCTION:NAME
  0   6796    write32:entry     115575
  0   6796    write32:entry     115575
  0   6796    write32:entry     115575
  0   6796    write32:entry     100392
  0   6796    write32:entry     100392
  0   6796    write32:entry     100392
```

Variables

- Idea: allow D actions to instantiate, manipulate, and record variables
- Variables can also be used by predicates to alter control flow and correlate events
- Variable species:
  - scalar variables: integers, strings
  - associative arrays: arbitrary (*key*, *value*) collections
- Variable scope:
  - global per client instance
  - thread-local per client instance

Sun microsystems

Scalar Variables in D

- Variables instantiated by D assignment operators: `= += -= *= /= %= &= ^= |= <<= >>= ++ --`
- Variable type determined by first assignment
- Variables initially assigned zeroes
- Definitions cached in libdtrace client state

ID	Name	Type	Scope
1	"foo"	int	global
2	"bar"	str	global
3	"baz"	int	thread

DIF

```
ldgs  1, %r1
...
```

1	"foo"	int	global
3	"baz"	int	thread

Variable Scope

- Global variables named by plain identifiers
- TLS variables accessed and instantiated by overloading “**`curthread->`**”
- D compiler precedence rules:
  - C type names defined in kernel (ANSI-C rules)
  - DTrace built-in variable names
  - Global and static variable names defined in kernel
  - User-defined variable names

Associative Arrays in D

- Arrays named by *identifier* [*expression-list*]
- Initially filled with zeroes just like scalars
- Entry can be freed by setting it to zero
- Type signature of key and value determined by first assignment; enforced thereafter
- Examples:

```
uids[curthread->t_procp->p_cred->cr_uid]++;
a[curthread, args[0]] = args[1];
```

Value Consistency

- Important to provide semantic consistency for data used in *both* predicate and actions:

```
/ foo == 3 / { trace(foo) }
/ dnlc_nentries < 10 / { trace(dnlc_nentries) }
```

- Kernel data consistency can be achieved by taking a snapshot prior to ECB processing
- Variables pose greater challenges:

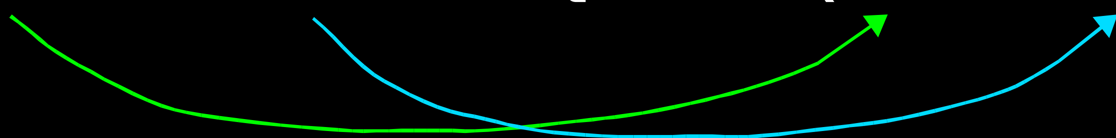
```
/ dnlc_nentries < 10 / { foo = 0 }
/ foo++ && bar++ / { trace(foo + bar) }
```

Variable Consistency

- Variable group must be self-consistent and consistent w.r.t. other modifying ECBs:

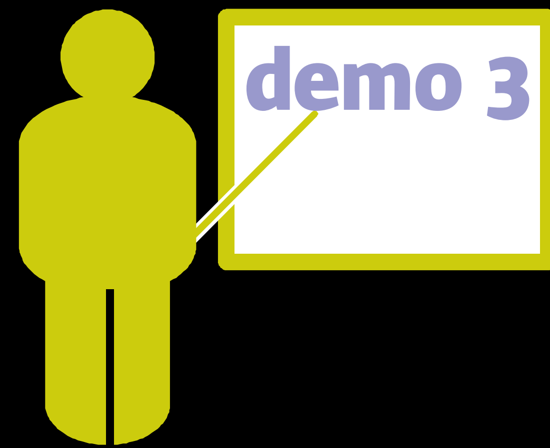
```
/ dnlc_nentries < 10 / { foo = 0 }

/ foo++ && bar++ / { trace(foo + bar) }
```



- Consistency is achieved by locking variables in a defined order (by ID)
- Only need to do this when variables are used in both predicate and action

dtrace(1M) syntax



dtrace [-i *id* [*predact*]]
[-P *prov* [*predact*]]
[-m [*prov*:] *mod* [*predact*]]
[-f [[*prov*:] *mod*:] *func* [*predact*]]
[-n [[[*prov*:] *mod*:] *func*:] *name* [*predact*]]

predact ⇒ [/ *predicate* /] { *action* }

Aggregations

- An *aggregating function* is a function $f(x)$, where x is a sequence of arbitrary length, for which there exists an aggregating function $f'(x)$ such that:

$$f'(f(x_0), f(x_1), \ldots f(x_n)) = f(x_0, x_1, \ldots x_n)$$

- E.g., COUNT, MEAN, MAXIMUM, and MINIMUM are aggregating functions; MEDIAN, and MODE are not

Aggregations, cont.

- When data is to be processed using an aggregating function, the implementation can be made very efficient:
  - Trace records need not be generated; only the intermediate results from the aggregating function need to be stored
  - Intermediate results from aggregating functions can be stored *per CPU*, thereby eliminating data sharing
  - Aggregating function can be periodically performed on all per CPU intermediate results to derive system-wide result

Aggregations, cont.

- An *aggregation* is an associative table keyed by an n-tuple where each value is the result of an aggregating function
- n-tuple consists of a list of D expressions
- Aggregating functions are provided by the framework
- Framework provides a single aggregation per consumer

Sun microsystems

Aggregations, cont.

- Current aggregating functions:
  - MAX(*expr*): the intermediate result is set to the greater of the intermediate result and *expr*
  - COUNT: increments the intermediate result
  - QUANTIZE(*expr*): the intermediate result consists of 64 power-of-two buckets; the bucket corresponding to *expr* is incremented
  - AVG(*expr*): the intermediate result consists of a count and a total; the count is incremented and the total is increased by *expr*

Aggregation Example

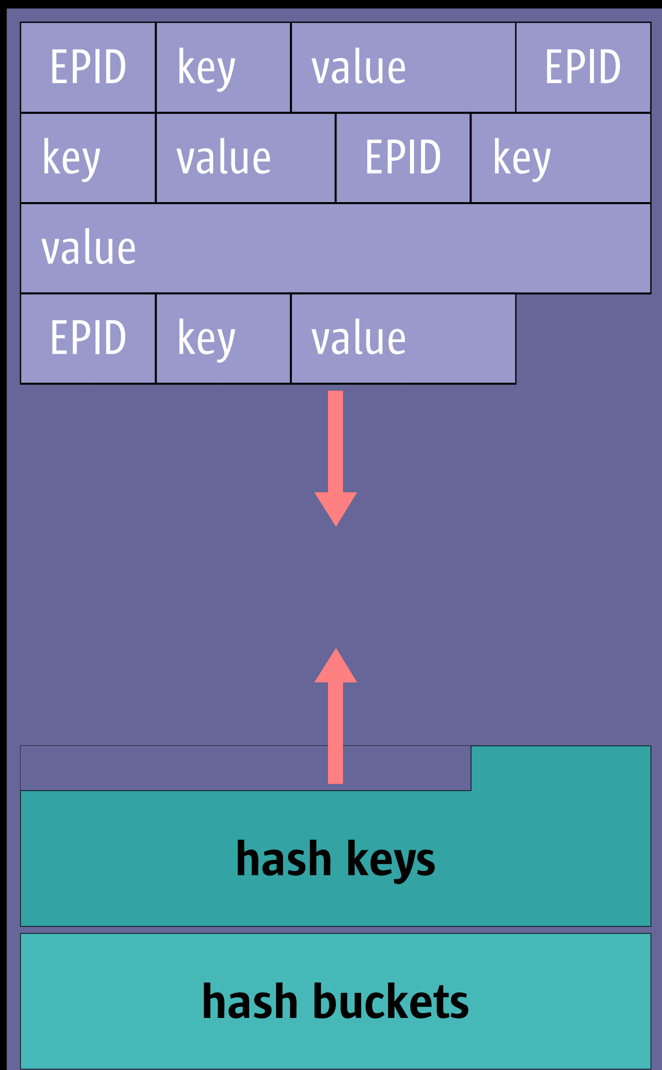
- For example, maximum kernel **`bcopy`**() size by command name:
  - Enable probe with function “**`bcopy`**”, name “**`entry`**”
  - Aggregate on:

    `curthread->t_procp->p_user.u_comm`
  - Set aggregating function to “**`max(arg2`**)”

Aggregation Implementation

- Aggregations are implemented using the same buffer infrastructure as trace buffers
- Buffer switching and copying thus fall out
- Aggregations are an associative table; buffering is complicated by the presence of hash table metadata

Aggregation Implementation

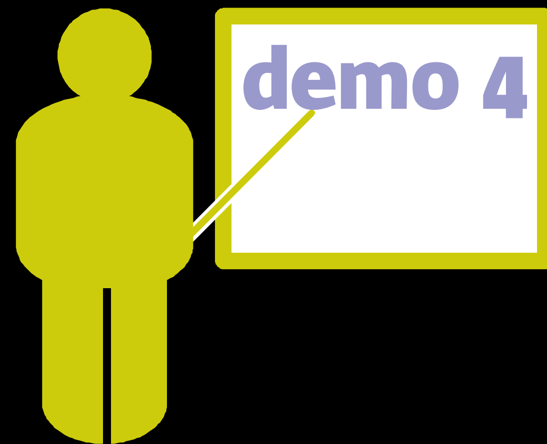


- *Data* grows from start of buffer
- *Metadata* grows from end of buffer
- *Only* data is copied out
- EPID is in data record, but is *not* considered to be part of the key

Aggregation Implementation

- Library applies aggregating function to consumed data, using formerly consumed data as intermediate result
- Allows the kernel to discard the metadata contents of consumed aggregation buffers
- Allows drops to be easily eliminated in long-running aggregations

dtrace(1M) syntax



dtrace [-i *id* [*aggact*]]
[-P *prov* [*aggact*]]
[-m [*prov*:] *mod* [*aggact*]]
[-f [[*prov*:] *mod*:] *func* [*aggact*]]
[-n [[[*prov*:] *mod*:] *func*:] *name* [*aggact*]]

aggact ⇒ [/ *predicate* /]
"[" *expr-list* "]" = *aggregating-func* (*arg-list*)

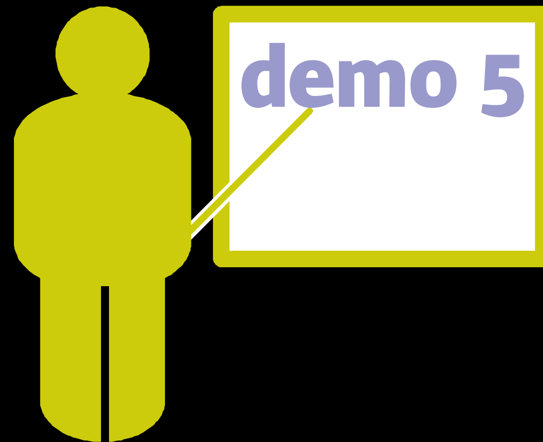
DTrace During Boot

- Normally, consumer is a process with DTrace pseudodevice open
- However, would like to be able to trace during boot — *before* processes can run
- Introduce *anonymous* state:
  - Predicates and actions for anonymous state are specified via driver's configuration file
  - Command has option to generate configuration file
  - Anonymous state may later be *grabbed* by a consuming process

DTrace During Boot, cont.

- Use of DTrace during boot revealed that each *text* page for **`libc`** is retrieved from disk three times! (see 4647351)
- Using probe in **`page_destroy`**() with an appropriate predicate revealed source to be calls to **`ufs_flush`**()
- **`ufs_flush`**() is called in **`fsck`**(1M) and again before remount of root filesystem
- Fixing this is a huge win: 8 seconds on X1

dtrace(1M) syntax



dtrace

-a - claim anonymous state

-A - generate .conf file for anonymous tracing

Lockstat Provider

- Lockstat provider implements hot patching of synchronization primitives
- Provides "**`block`**," "**`spin`**," "**`acquire`**" and "**`release`**" probes for **`mutex_enter`**(), **`rw_enter`**(), etc.
- **`lockstat`**(1M) will be reimplemented as a DTrace consumer
- Long-standing RFEs (e.g., lock statistics per thread or per process) simply fall out

Profile Provider

- Provides unanchored probes based on profile interrupt
- Probes implemented as high level cyclics
- Currently no way to specify arbitrary rate; provider makes available ten probes with different hard-coded rates
- Arbitrary rates may be available via private consumer/provider interface

TL>0 Provider

- UltraSPARC-specific provider will be implemented to allow probes when trap level (TL) is greater than zero
- Non-trivial: **`dtrace_probe`**() cannot be called from TL>0 context
- Provider will use dynamic trap table interposition, as used in **`trapstat`**(1M), **`ttrace`** and **`atrace`**

TL>0 Provider, cont.

- Implementation will be excruciating, but payoff is substantial:
  - Huge quantity of data available via trap table interposition
  - Will benefit enormously from DTrace's ability to prune and coalesce data
- Using technology first developed in **`atrace`**, TL>0 provider will be able to optionally provide address traces

TL>0 Provider, Cont.

- `trapstat`(1M) will be reimplemented as a DTrace consumer
- **TRAPTRACE** will be obviated; equivalent functionality will be dynamic
- Example questions answered:
  - TLB misses per process, per page
  - Window spill traps on a per-function basis
  - All memory references in a specific function for a specific process

Probes in C Source Code

- Permit users to define probes in C source as TNF and VTRACE did, but improve syntax:

```
TNF_PROBE_5(strategy, "io blockio", /* CSTYLED */,
        tnf_device,     device,         bp->b_edev,
        tnf_diskaddr,   block,          bp->b_lblkno,
        tnf_size,       size,           bp->b_bcount,
        tnf_opaque,     buf,            bp,
        tnf_bioflags,   flags,          bp->b_flags);
```

- Probe should look like a normal function call
- Enhance compiler to handle code generation and argument type descriptions

Traditional Approaches

- D-cache hot but inflexible:

```
if (tracing_on)
        trace(arg1, arg2, ...);
```

- D-cache cold but more flexible:

```
if (this_probe_on)
        trace(arg1, arg2, ...);
```

- Both implementations bloat I-cache footprint

Compiler-Assisted Approach

```
maj = getmajor(bp->b_edev);
...

ldx  [%i0 + 0xa8], %g2  ! bp->b_edev
mov  -1, %g3
srl  %g3, 0, %g3
srlx %g2, 0x20, %g2
and  %g2, %g3, %g2      ! %g2 = getmajor(b_edev)
...
ret
restore %g0, 0, %o0     ! return (0);
```

Compiler-Assisted Approach

```
TRACE("myprobe", bp);
maj = getmajor(bp->b_edev);
...

ldx  [%i0 + 0xa8], %g2  ! treat as potential call
mov  -1, %g3
srl  %g3, 0, %g3
srlx %g2, 0x20, %g2
and  %g2, %g3, %g2      ! %g2 = getmajor(b_edev)
...
ret
restore %g0, 0, %o0     ! return (0);
nop                     ! patch point for branch
mov  %i0, %o0           ! assemble probe argument
.stabs "myprobe", id, location, arg-type, ...
```

Compiler-Assisted Approach

```
TRACE("myprobe", bp);
maj = getmajor(bp->b_edev);
...

ba,a args1                    ! branch to arg assembly
mov  -1, %g3
srl  %g3, 0, %g3
srlx %g2, 0x20, %g2
and  %g2, %g3, %g2            ! %g2 = getmajor(b_edev)
...
ret
restore %g0, 0, %o0           ! return (0);
call trampoline               ! jump to trampoline code
mov  %i0, %o0                 ! assemble argument
.stabs "myprobe", id, location, arg-type, ...
```

C Probe Applications

- Probes in C source code can be used to convert all kernel ASSERT() instances into probes that can be enabled in production
- Probes can also be placed in C source code to facilitate fault injection testing
- Debug printf code that is not replaced by FBT probes can be replaced with C probes

Basic Block Tracing

- Compiler -xa (tcov) and -xpg (gprof) options generate instrumented code that can be used for basic block coverage, profiles
- DTrace “BBT” provider can be implemented to publish block sites as DTrace probes
- Kernel modules can be compiled using these options for coverage testing
- RIP: uts/common/os/unix_bb.c

Fast-Trap Tracing

- DTrace will reserve fast-trap entry point(s) for tracing user-level activities
- DTrace “FTT” provider can also provide limited access to set of input arguments
- Traps can be generated using handcoded assembly or libc assembly wrapper
- Traps can also be inserted by user-level code generators (e.g. HotSpot JVM)

Interface Stability

- Problem: want to allow tools outside of O/N to reliably layer on top of DTrace
- Extend probe description tuple to include probe *stability* (i.e. attributes(**5**) data)
- Most of kernel is Unstable, but DDI routines and types can be Evolving
- D compiler can provide a “lint” mode to warn developers of unstable dependencies

Stable Abstractions

- We can also create more stable abstractions at DTrace API layer, e.g. proc(**4**) structures
- Compiler could provide **`proc_t *psinfo`**
- Library performs necessary transformations:

```
psinfo->pr_flag ⇒ curthread->t_procp->p_flag
psinfo->pr_nlwp ⇒ curthread->t_procp->p_lwpcnt
psinfo->pr_uid ⇒ curthread->t_procp->p_cred->cr_uid
psinfo->pr_sid ⇒ curthread->t_procp->p_sessp->s_sid
...
```

Translators

- TNF users burdened with task of translating between abstraction and implementation:
  - ls -lL /dev/dsk/* to deal with dev_t mappings
  - PIDs/LWP ids ⇔ proc_t/klwp_t addresses
  - filenames ⇔ vnode_t addresses, inode numbers
- DTrace could support pluggable translators in or out of kernel to handle mappings
- D compiler can attempt to map predicate to available state by searching for translation

Trace Files

- DTrace will provide efficient access to saved trace data and data formatting features
- DTrace library will provide stable API for reading and writing trace files
- Lesson from crash dumps: put *everything* needed to interpret data in the trace file
- Files from one system, OS revision should be readable on another system or OS revision

File Format

File header and meta-data for each trace record generated in advance

- ASCII and DIF predicate
- EPID record description
- data length
- data types

Probe data can be streamed out to file using record id while tracing active

- module name, id
- symbol table
- string table
- CTF section

- Module cache of symbol and type data can be written once tracing is complete

Conclusion

Feature	GTF	vtrace	TNF	KInst	DProbe	DTrace
user/kernel/merged	M	M	M	K	K	M
probe coverage	●	◒	✗	◒	◒	●
disabled probe effect	○	✗	○	●	●	●
scalability	○	●	○	○	○	●
safety	●	●	◒	✗	✗	●
extensibility	◒	○	○	◒	◒	●
data filtering	●	✗	✗	○	●	●
arbitrary recording	✗	✗	✗	○	●	●
self describing	◒	○	◒	✗	✗	●
run-time analysis	●	✗	✗	●	◒	●
stock availability	●	✗	●	◒	◒	●
stable abstractions	◒	◒	●	✗	✗	●

For more information ...

- Copies of this presentation and other documents available at http://dtrace.eng
- Questions to dtrace-interest@kiowa.eng
- E-mail dtrace-interest-admin@kiowa.eng to join the interest list
- Meetings for near-term consumers
- Project documentation, schedules, and other information forthcoming

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