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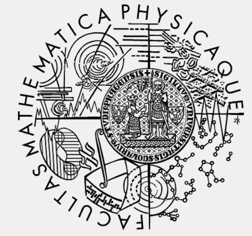

Crash Dump Analysis

DTrace & SystemTap

Jakub Jermář
Martin Děcký

DTrace

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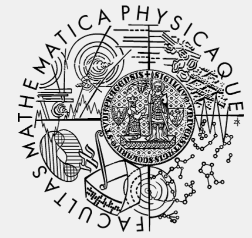

- Dynamic Tracing
  - Observing production systems
    - Safety
    - Zero overhead if observation is not activated
    - Minimal overhead if observation is activated
    - No special debug/release builds
  - Merging and correlating data from multiple sources
    - Total observability
      - Global view of the system state

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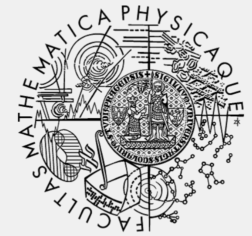
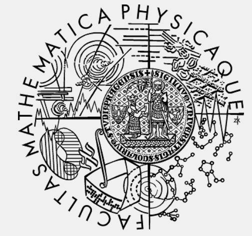


Terminology

- Probe
  - A place in code or an event which can be observed
    - If a probe is activated and the code is executed (or the event happens), the probe is fired
      - A special script written in D language is executed
- Provider
  - Registers probes to DTrace infrastructure
    - Does the *dirty work* of activation, tracing and inactivation
- Consumer
  - Consumes and postprocesses the data from fired probes

Overview



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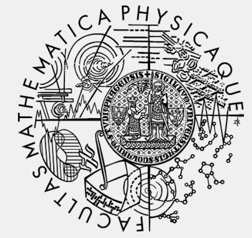

DTrace history

- 31st January 2005
  - Official part of Solaris 10
    - Released as open source (CDDL)
      - First piece of OpenSolaris to be released
- 27th October 2007
  - Ported to Mac OS X 10.5 (Leopard)
- 2nd September 2008
  - Ported to FreeBSD 7.1 (released 6th January 2009)
- 21st February 2010
  - Ported to NetBSD (only for i386, not enabled by default)

DTrace history (2)

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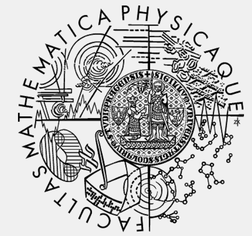
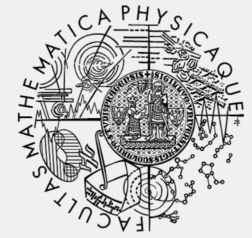


- Linux
  - Cannot be directly integrated (CDDL vs. GPL)
  - Beta releases (since 2008)
    - Standalone kernel module with no modifications to core sources
    - Only some providers (fbt, syscall, usdt)
    - Development snapshots available regularly
  - *SystemTap*
    - Linux-native analogy
    - A script in *SystemTap language* is converted to a C source code of a kernel module
      - Loaded and executed natively in the running kernel
      - Embedded C enabled in guru mode



DTrace history (3)

- QNX
  - Port in progress
- 3rd party software with DTrace probes
  - Apache
  - MySQL
  - PostgreSQL
  - X.Org
  - Firefox
  - Oracle JVM
  - Perl, Ruby, PHP

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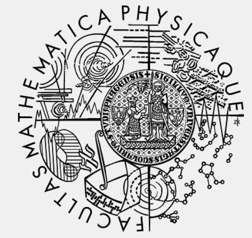

D language

```
probe /predicate/ {
    actions
}
```

- Describe what is executed if a probe fires
  - Similar to C or AWK
    - Without dangerous constructs (branching, loops, etc.)
  - Many of the fields can be absent
    - Default predicate/action

D probes

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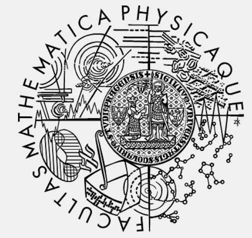


```
probe /predicate/ {
   actions
}
```

- A pattern consisting of fields split by colon
  - **provider**:**module**:**function**:**name**
    - Fields can be omited (other are read from right to left)
      - foo:bar — match function *foo* and name *bar* in all modules provided by all providers
    - Fields can be empty (interpreted as *any*)
      - syscall::: — match all probes provided by the *syscall* provider

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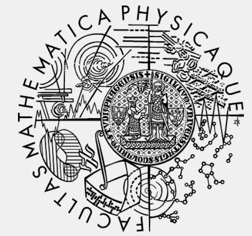
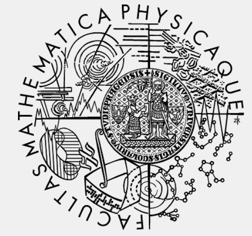


D probes (2)

```
probe /predicate/ {
   actions
}
```

- Shell pattern matching
  - Wild characters *, ?, []
    - Can be escaped by \
    - syscall::*lwp*:entry — match all probes provided by the *syscall* provider, in any module, in all functions (syscalls) containing the string *lwp* and matching syscall *entry* points
- Special probes
  - BEGIN, END, ERROR
    - Implemented by *dtrace* provider



D probes (3)

```
probe /predicate/ {
   actions
}
```

- Displaying all configured probes

```
dtrace -l
```

D predicates

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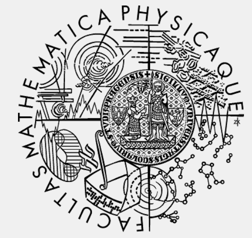
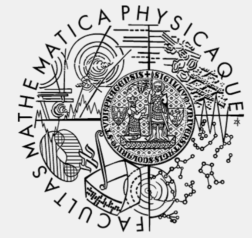



```
probe /predicate/ {
    actions
}
```

- Boolean expression guarding the actions
  - Any expression which evaluates as integer or pointer
    - Zero is considered as false, non-zero as true
    - Any D operators, variables and constants
    - Can be absent
      - Implicitly true

D actions



```
probe /predicate/ {
   actions
}
```

- List of statements
  - Separated by semicolon
  - No branching, no loops
  - Default action if empty
    - Usually the probe name is printed out

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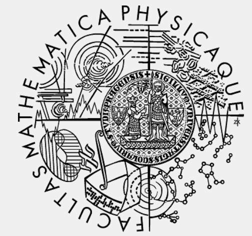
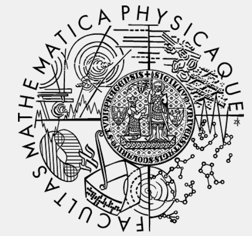


D types

- Basic data types reflect C language
  - Integer types and aliases
    - (unsigned/signed) char, short, int, long, long long
    - int8_t, int16_t, int32_t, int64_t, intptr_t, uint8_t, uint16_t, uint32_t, uint64_t, uintptr_t
  - Floating point types
    - float, double, long double
      - Values can be assigned, but no floating point arithmetics is implemented in DTrace



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D types (2)

- Derivated and special data types
  - Pointers
    - C-like pointers to other data types (including pointer arithmetics)
      - int *value; void *ptr;
        - Constant *NULL* is zero
      - DTrace enforces weak pointer safety
        - Invalid memory accesses are fully handled
        - However, this does not provide reference safety as in Java

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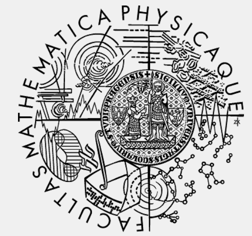
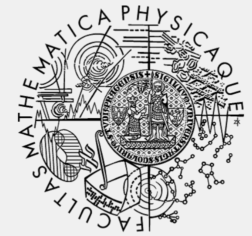


D types (2)

- Scalar arrays
  - C-like arrays of basic data types
    - Similar to pointers, but can be assigned as a whole
    - int values[5][6];
- Strings
  - Special type descriptor string (instead of char *)
    - Can be assigned as a whole by value (char * copies reference)
    - Represented as NULL-terminated character arrays
    - Internal strings are always allocated as bounded
      - Cannot exceed the predefined maximum length (256 bytes)

D types (3)



- Composed data types
  - Structures
    - Records of several other types
    - Type declared in a similar way as in C
    - Variables must be declared explicitly
    - Members are accessed via . and -> operators

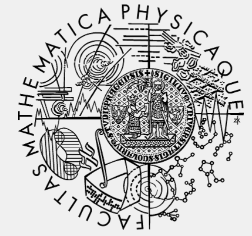
```
struct callinfo {
    uint64_t ts;
    uint64_t calls;
};

struct callinfo info[string];

syscall::read:entry,
syscall::write:entry {
    info[probefunc].ts = timestamp;
    info[probefunc].calls++;
}

END {
    printf("read  %d %d\n",
        info["read"].ts,
        info["read"].calls);
    printf("write %d %d\n",
        info["write"].ts,
        info["write"].calls);
}
```

D types (4)



- Unions
- Bit-fields
- Enumerations
- Typedefs
  - All similar as in C
- Inlines
  - Typed constants
    - inline string desc = "something";

```
enum typeinfo {
    CHAR_ARRAY = 0,
    INT,
    UINT,
    LONG
};

struct info {
    enum typeinfo disc;
    union {
        char c[4];
        int32_t i32;
        uint32_t u32;
        long l;
    } value;

    int a : 3;
    int b : 4;
};

typedef struct info info_t;
```

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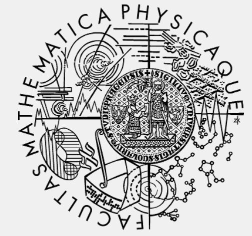

DTrace operators

- Arithmetic
  - + - * / %
- Relational
  - < <= > >= == !=
    - Works also on strings (lexical comparison)
- Logical
  - && || ^^ !
    - Short-circuit evaluation
- Bitwise
  - & | ^ << >> ~
- Assignment
  - = += -= *= /= %= &= |= ^= <<= >>=
    - Return values as in C
- Increment and decrement
  - ++ --

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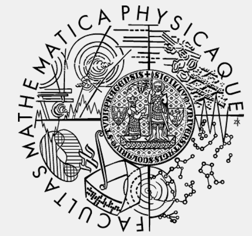
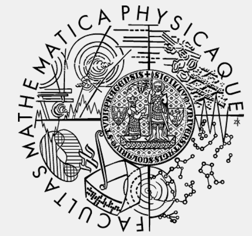


DTrace operators (2)

- Conditional expression
  - Replacement for branching (which is absent in D)
    - *condition* ? *true_expression* : *false_expression*
- Addressing, member access and sizes
  - & * . -> sizeof(*type/expr*) offsetof(*type*, *member*)
- Kernel variables access
  - `
- Typecasting
  - (int) x, (int *) NULL, (string) *expression*, stringof(*expr*)

DTrace variables

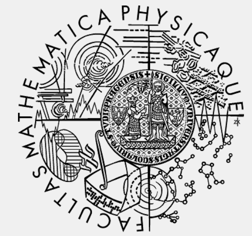


- Scalar variables
  - Simple global variables
    - Storing fixed-size data (integers, pointers, fixed-size composite types, strings with fixed-size upper bound)
    - Do not have to be declared (but can be), duck-typing

```
BEGIN {
    /* Implicitly declare
       an int variable */
    value = 1234;
}
```

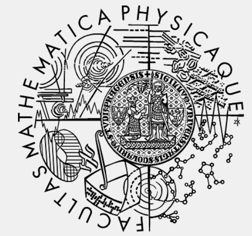
```
/* Explicitly declare an int
   variable (initial value
   cannot be assigned here) */
int val;

BEGIN {
    value = 1234;
}
```

DTrace variables (2)



- Associative arrays
  - Global arrays of scalar values indexed by a key
    - Key signature is a list of scalar expression values
      - Integers, strings or even a tuple of scalar types
      - Each array can have a different (but fixed) key signature
      - Declared implicitly by assignment or explicitly
        - `values[123, "key"] = 456;`
    - All values have also a fixed type
      - But each array can have a different value type
      - Declared implicitly by assignment or explicitly
        - `int values[unsigned int, string];`

DTrace variables (3)

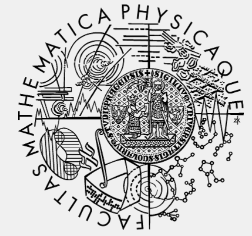


- Thread-local variables
  - Scalar variables or associative arrays specific to a given **thread**
    - Identified by a special identifier *self*
    - If no value has been assigned to a thread-local variable in the given thread, the variable is considered zero-filled
      - Assigning zero to a thread-local variable deallocates it

```
syscall::read:entry {
    /* Mark this thread */
    self->tag = 1;
}
```

```
/* Explicit declaration */
self int tag;

syscall::read:entry {
    self->tag = 1;
}
```

DTrace variables (4)



- Clause-local variables
  - Scalar variables or associative arrays specific to a given **probe clause**
    - Identified by a special identifier *this*
    - They are not initialized to zero
      - The value is kept for multiple clauses associated with the same probe

```
syscall::read:entry {
    this->value = 1;
}
```

```
/* Explicit declaration */
this int value;

syscall::read:entry {
    this->value = 1;
}
```

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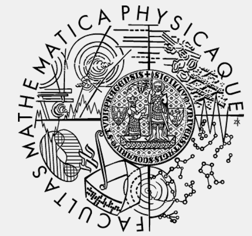


DTrace aggregations

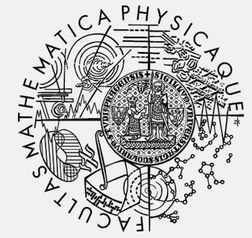
- Variables for storing statistical data
  - Storing values of aggregative data computation
    - For aggregating functions *f*(...) which satisfy the following property

$$f(f(x_0) \cup f(x_1) \cup \ldots \cup f(x_n)) = f(x_0 \cup x_1 \cup \ldots \cup x_n)$$

  - Aggregations are declared in a simular way as associative arrays

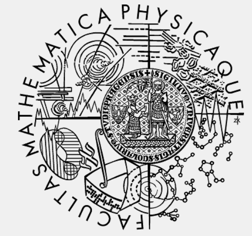
```
@values[123, "key"] = aggfunc(args);
@_[123, "key"] = aggfunc(args);  /* Simple variable */
@[123, "key"] = aggfunc(args);   /* dtto */
```

DTrace aggregations (2)



- Aggregation functions
  - count()
  - sum(*scalar*)
  - avg(*scalar*)
  - min(*scalar*)
  - max(*scalar*)
  - lquantize(*scalar*, *lower_bound*, *upper_bound*, *step*)
    - Linear frequency distribution
  - quantize(*scalar*)
    - Power-of-two frequency distribution

DTrace aggregations (3)



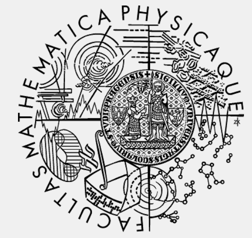
- By default aggregations are printed out in END

```
syscall:::entry {
    @counts[probefunc] = count();
}

# dtrace -s counts.d
dtrace: script 'counts.d' matched 235 probes
^C

  resolvepath                                                       8
  lwp_park                                                         10
  gtime                                                            12
  lwp_sigmask                                                      16
  stat64                                                           46
  pollsys                                                          93
  p_online                                                        256
  ioctl                                                          1695
#
```

DTrace built-in variables



- Global variables defined by DTrace
  - Contain various state-dependent values
    - int64_t arg0, arg1, ..., arg9
      - Input arguments for the current probe
    - args[]
      - Typed arguments to the current probe (e.g. the syscall arguments with the appropriate types)
    - uintptr_t caller
      - Instruction pointer of the code just before firing the probe
    - kthread_t *curthread
      - Current thread kernel structure

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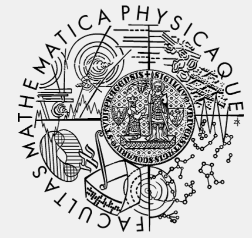
DTrace built-in variables (2)



- string cwd
  - Current working directory
- string execname
  - Name which was used to execute the current process
- pid_t pid, tid_t tid
  - Current PID, TID
- string probeprov, probemod, probefunc, probename
  - Current probe provider, module, function and name

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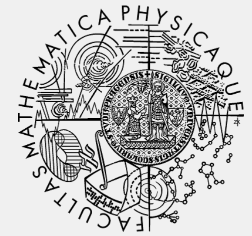

Using action statements

- DTrace records output to a *trace buffer*
  - Most of the action statements produce some sort of output to the trace buffer
    - trace(*expr*)
      - Output value of an expression
    - tracemem(*address*, *bytes*)
      - Copy given number of bytes from the given address to the buffer
    - printf(*format*, *...*)
      - Output formatted strings (format options covered later)
      - Safety checks

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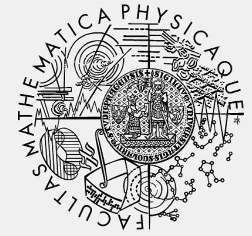


Using action statements (2)

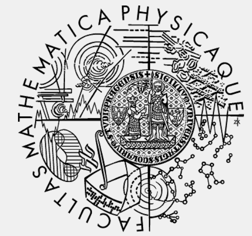
- printa(*aggregation*)

  printa(*format*, *aggregation*)
  - Start processing *aggregation* data
    - Parallel to other execution (output can be delayed)
- stack()

  stack(*frames*)
  - Output kernel stack trace
- ustack()

  ustack(*frames*)
  - Output user space stack trace
  - Addresses are not looked up by the kernel, but by the user space consumer (later)

Using action statements (3)

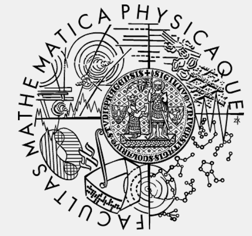


- ustack(*frames*, *string_size*)
  - Output user space stack trace with symbol lookup (in kernel)
    - The kernel allocates *string_size* bytes for the output of the symbol lookup
    - The probe provider must annotate the user space stack with run-time symbol annotations to make the lookup possible
      - Currently only JVM (1.5 or newer) supports this
- jstack()

  jstack(*frames*)

  jstack(*frames*, *string_size*)
  - Alias for ustack() with non-zero default *string_size*

printf() formatting



- Conversion formats
  - %a
    - Pointer as kernel symbol name
  - %c
    - ASCII character
  - %C
    - Printable ASCII or escape
  - %d, %i, %o, %u, %x
  - %e
    - Float as [**-**]*d***.***ddd***e±***dd*
  - %f
    - Float as [**-**]*ddd***.***ddd*
  - %p
    - Hexadecimal pointer
  - %s
    - ASCII string
  - %S
    - ASCII string or escape

Subroutines

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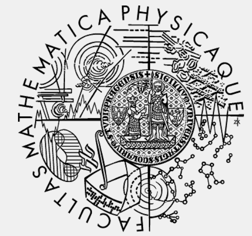
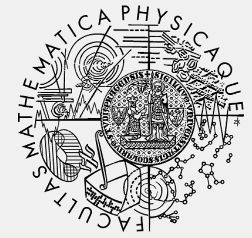
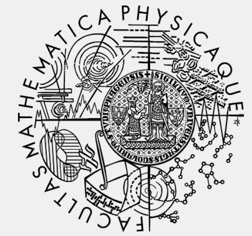


- Special actions which alter the state of DTrace
  - But do not produce any output to the trace buffer
  - Are completely safe
    - Usually manipulate the local memory storage of DTrace
    - *alloca(*size*)
      - Allocate *size* bytes of scratch memory
      - The memory is released after the current clause ends
    - bcopy(**src*, **dest*, *size*)
      - Copy *size* bytes from outside scratch memory to scratch memory

Subroutines (2)



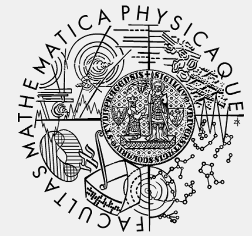
- *copyin(*addr*, *size*)
  - Copy size bytes from the user memory of the current process to scratch memory
- *copyinstr(*addr*)
  - Copy NULL-terminated string from the user memory of the current process to scratch memory
- mutex_owned(**mutex*)
  - Tell whether a kernel mutex is currently locked or not
- *mutex_owner(**mutex*)
  - Return the pointer to kthread_t of the thread which owns the given mutex (or NULL)
- mutex_type_adaptive(**mutex*)



Subroutines (3)

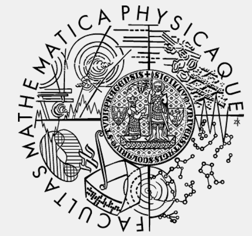
- strlen(*string*)
  - Return length of a NULL-terminated string
- strjoin(**str*, **str*)
  - Concatenate two NULL-terminated strings
- basename(**str*)
  - Return a basename of a given filename
- dirname(**str*)
- cleanpath(**str*)
  - Return a filesystem path without elements such as **../**
- rand()
  - Return a (weak) pseudo-random number

Destructive actions



- Changing the state of the system
  - In a deterministic way
    - But it can be still dangerous in production environment
    - Need to be explicitly enabled using `dtrace -w`
    - stop()
      - Stop the current process (e.g. to dump the core or attach mdb)
    - raise(*signal*)
      - Send a signal to the current process
    - panic()

Destructive actions (2)



- copyout(**buffer*, *addr*, *bytes*)
  - Store given number of bytes from a buffer to the given address
  - Page faults are detected and avoided
- copyoutstr(*string*, *addr*, *maxlen*)
  - Store at most *maxlen* bytes from a NULL-terminated string to the given address
- system(*program*, ...)
  - Execute a program as it would be executed by a shell (*program* is actually a printf() format specifier)
- breakpoint()
  - Induce a kernel breakpoint (if a kernel debugger is loaded, it is executed)

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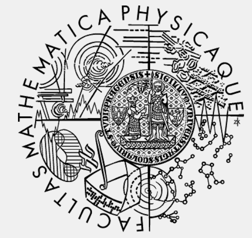
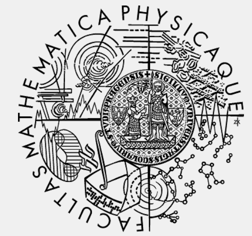


Destructive actions (3)

- chill(*nanoseconds*)
  - Spin actively for a given number of nanoseconds
  - Useful for analyzing timing bugs
- exit(*status*)
  - Exit the tracing session and return the given status to the consumer

Speculative tracing



- Predicates are good for filtering out unimportant probes **before** they are fired
- But how to effectively filter out unimportant probes eventually some time **after** they are fired?
  - You can tell that you are interested in the data from a probe *n* only after probe *n*+*k* ($k > 0$) is fired
  - Solution: *Speculatively* record all the data, but decide later whether to *commit* it or not

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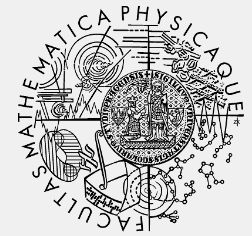

Speculative tracing (2)

- speculation()
  - Create a new speculative buffer and return its ID
  - By default the number of speculative buffers is limited to 1
- speculate(*id*)
  - The rest of the clause will be recorded to the speculative buffer given by *id*
  - This must be the first data processing action in a clause
  - Disallowed actions: aggregating, destructive
- commit(*id*)
  - Commit the speculative buffer given by *id* to the trace buffer

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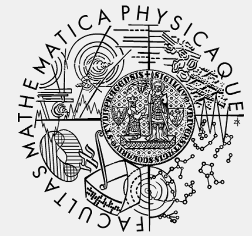
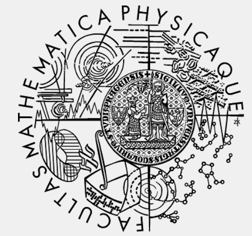


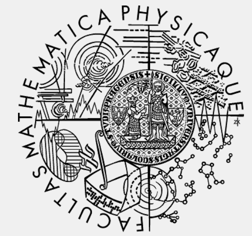
Provider: *syscall*

- Tracing of kernel system calls
  - Probes for entry and exit points of a syscall
    - Access to (typed) arguments
    - Access to the return value (on exit)
    - Access to kernel errno
    - Access to kernel variables
  - Internally uses the original syscall tracing mechanism



Provider: *fbt*

- Function boundary tracing
  - Probes on function entry point and (all) exit points of almost all kernel functions
    - Inlined and leaf functions cannot be traced
  - In *entry*
    - All typed function arguments can be accessed via args[]
  - In *return*
    - Offset of the return instruction is stored in arg0
    - Typed return value is stored in args[1]



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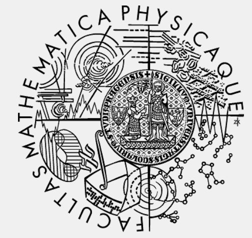
Provider: *fbt* (2)

- How does it work?

```
ufs_mount:           pushq %rbp             int $0x3
ufs_mount+1:         movq %rsp,%rbp         movq %rsp,%rbp
ufs_mount+4:         subq $0x88,%rsp        subq $0x88,%rsp
ufs_mount+0xb:       pushq %rbx             pushq %rbx
......
ufs_mount+0x3f3:     popq %rbx              popq %rbx
ufs_mount+0x3f4:     movq %rbp,%rsp         movq %rbp,%rsp
ufs_mount+0x3f7:     popq %rbp              popq %rbp
ufs_mount+0x3f8:     ret                    int $0x3
```

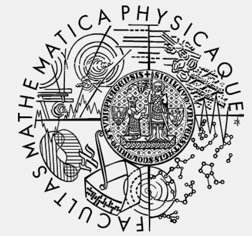
uninstrumented | instrumented

Provider: *sdt*



- Static kernel probes
  - Probes declared on arbitrary places in the kernel code (via a macro)
  - Currently just a few of them actually defined
    - *interrupt-start*

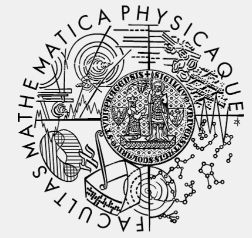
      interrupt-complete
      - arg0 contains pointer to dev_info structure



Provider: *sdt* (2)

- How does it work?

	uninstrumented	instrumented
`squeue_enter_chain+0x1af:`	`xorl %eax,%eax`	`xor %eax,%eax`
`squeue_enter_chain+0x1b1:`	`nop`	`nop`
`squeue_enter_chain+0x1b2:`	`nop`	`nop`
`squeue_enter_chain+0x1b3:`	`nop`	`lock nop`
`squeue_enter_chain+0x1b4:`	`nop`	
`squeue_enter_chain+0x1b5:`	`nop`	`nop`
`squeue_enter_chain+0x1b6:`	`movb %bl,%bh`	`movb %bl,%bh`



Provider: *proc*

- Probes corresponding to process and thread life-cycle
  - Creating a process (using fork() and friends)
  - Executing a binary
  - Exiting a process
  - Creating a thread, destroying a thread
  - Receiving signals

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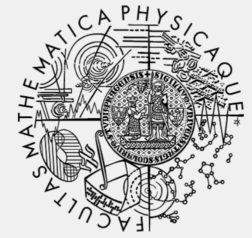

Provider: *sched*

- Kernel scheduler abstraction probes
  - Changing of priorities
  - Thread being scheduled
  - Thread being preempted
  - Thread going to sleep
  - Thread waking up

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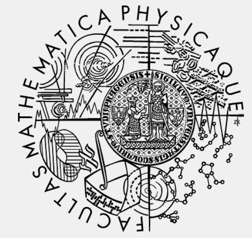

Provider: *io*

- Input/output subsystem probes
  - Starting an I/O request
  - Finishing an I/O request
  - Waiting for a device

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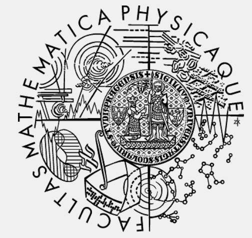

Provider: *pid*

- Tracing user space functions
  - Does not enforce serialization
    - Traced process in never stopped
    - Boundary probes similar to *fbt*
      - Function *entry* and *return*
        - Arguments in arg0, arg1, ... arg9 are raw unfiltered int64_t values
    - Arbitrary function offset
    - User space symbol information is required to support symbolic function names
      - On Solaris, standard shared libraries contain symbol information

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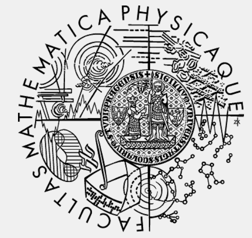
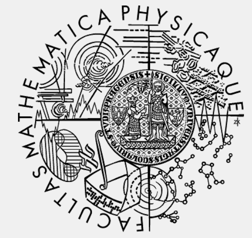


Other providers

- Many other providers exist
  - Application specific providers (X.Org, PostgreSQL, Firefox, etc.)
    - Via DTrace *total observability* you can correlate information such as which SQL transaction is generating a particular I/O load in the kernel
  - VM based providers (JVM, PHP, Perl, Ruby)
  - More kernel providers
    - Memory management provider (*vminfo*)
    - Network stack provider (*mid*)
    - Profiling provider (*profile*)
      - Interval-based probes



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DTrace and mdb

- Accessing DTrace data from a crash dump
  - Analyzing DTrace state
    - Display trace buffers, consumers, etc.

```
> ::dtrace_state
    ADDR MINOR     PROC NAME                  FILE
ccaba400     2        - <anonymous>              -
ccab9d80     3 d1d6d7e0 intrstat          cda37078
cbfb56c0     4 d71377f0 dtrace            ceb51bd0
ccabb100     5 d713b0c0 lockstat          ceb51b60
d7ac97c0     6 d713b7e8 dtrace            ceb51ab8
```

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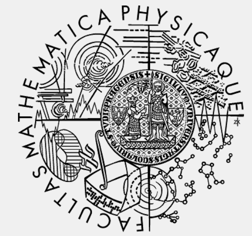
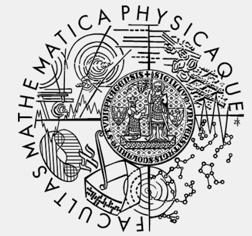


DTrace and mdb (2)

- Displaying the contents of a trace buffer

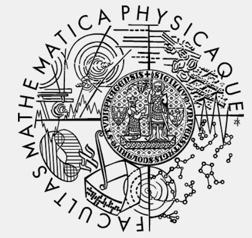
```
> ccaba400::dtrace
CPU     ID                    FUNCTION:NAME
  0    344             resolvepath:entry   init
  0     16                   close:entry   init
  0    202                   xstat:entry   init
  0    202                   xstat:entry   init
  0     14                    open:entry   init
  0    206                  fxstat:entry   init
  0    186                    mmap:entry   init
  0    186                    mmap:entry   init
  0    186                    mmap:entry   init
  0    190                  munmap:entry   init
  0    344             resolvepath:entry   init
  0    216                 memcntl:entry   init
  0     16                   close:entry   init
  0    202                   xstat:entry   init
...
```



DTrace and mdb (3)

- Interpretting the results
  - The output of `::dtrace` is the same as the output of `dtrace` utility
  - The order is always oldest to youngest within each CPU
  - The CPU buffers are displayed in numerical order (you can use `::dtrace -c cpu` to show only a specific CPU)
  - Only in-kernel data which has not yet been processed by an user space consumer can be displayed
    - To keep as much data as possible in the kernel buffer, the following dtrace options can be used

```
dtrace -s ... -b 64k -x bufpolicy=ring
```



Resources

- Richard McDougall, Jim Mauro, Brendan Gregg: *Solaris Performance and Tools: DTrace and MDB Techniques for Solaris 10 and OpenSolaris*
- *Solaris Dynamic Tracing Guide*
  - http://docs.sun.com/app/docs/doc/817-6223