Dynamic Linux Kernel Instrumentation with SystemTap

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Previous Linux Monitoring Tools

- Examples: ps, netstat, vmstat, iostat, sar, strace, top, oprofile, etc
- Drawbacks:
  - Application-centric tools are narrow in scope
  - Tools with system-wide scope present a static view of system behaviour but does not let you probe further
  - Many different tools and data sources but no easy way to integrate
- Many kinds of problems are not readily exposed by traditional tools:
  - Interactions between applications and the operating system
  - Interactions between processes and kernel subsystems
  - Problems that are obscured by ordinary behaviour and require examination of an activity trace

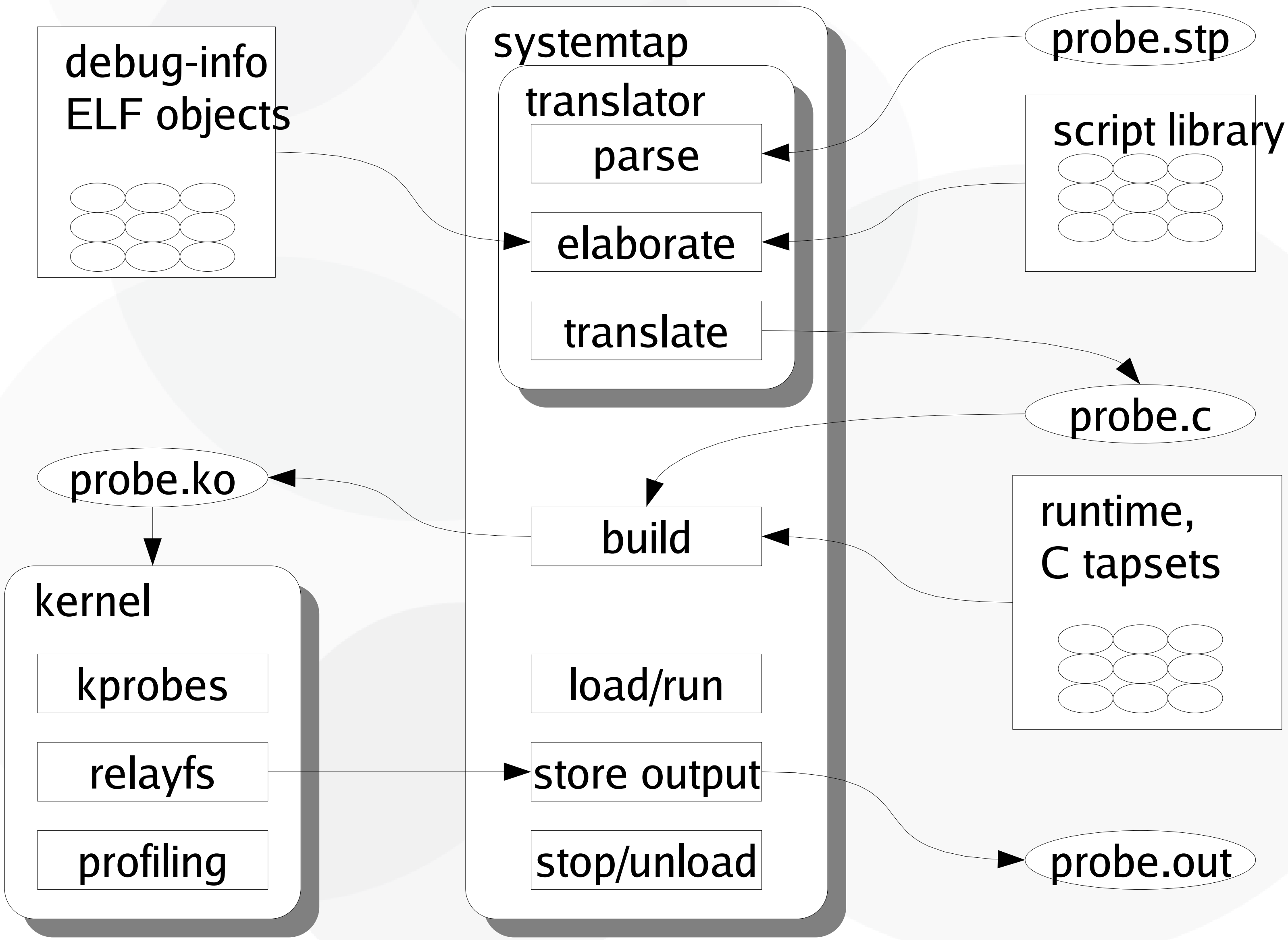
SystemTap

- A tool to enable a deeper look into a running system:
  - Provides a high-level script language to instrument unmodified running kernels
  - Exposes a live system activity and data
  - Provides performance and safety by careful translation to C
  - Includes growing library of reusable instrumentation scripts
- Started January 2005
- Free/Open Source Software (GPL)
- Active contributions from Red Hat, Intel, IBM, Hitachi, and others

SystemTap Target Audience

- Kernel Developer: I wish I could add a debug statement easily without going through the compile/build cycle.
- Technical Support: How can I get this additional data that is already available in the kernel easily and safely?
- Application Developer: How can I improve the performance of my application on Linux?
- System Administrator: Occasionally jobs take significantly longer than usual to complete, or do not complete. Why?
- Researcher: How would a proposed OS/hardware change affect system performance?

SystemTap Overall Diagram



Tapsets

- A tapset defines:
  - Probe points/aliases: symbolic names for useful instrumentation points
  - Useful data values that are available at each probe point
- Written in script and C by developers knowledgeable in the given area
- Tested and packaged with SystemTap

Runtime Library

- Implements some utilities:
  - Associative arrays, statistics, counters
  - Stack trace, register dump, symbol lookup
  - Safe copy from userspace
  - Output formatting and transport
- Could also be used by C programmers to simplify writing raw kprobes-based instrumentation

Kprobes

- C API to allow dynamic kernel instrumentation
- Probe Point: An instruction address in the kernel
- Probe Handler: An instrumentation routine, as function pointer
- Replace the instruction at the probe points with a breakpoint instruction
- When the breakpoint is hit, call the probe handler
- Execute the original instruction, then resume

Kprobes Limitations

- C API
- No checking that probe point is at instruction boundary
- Kprobes-based code is hard to maintain and port due to hard coding of addresses
- No library of probes for common tasks
- No convenient access to local variables
- Requires significant kernel knowledge

SystemTap Safety Goals

- For use in production environment – aiming to be crash-proof
- Uses existing compiler tool chain, kernel
- Safe mode: Restricted functionality for production
- Guru mode: Full feature set for development, debugging
- Static analyser:
  - Protection against translator bugs and users errors
  - Detects illegal instructions and external references

SystemTap Safety Features

- No dynamic memory allocation
- Types & types conversions limited
- No assembly or arbitrary C code (unless -g or Guru mode is used)
- Kernel functions known to crash system when probed are blacklisted
  - default_do_nmi, __die, do_int3, do_IRQ, do_page_fault, do_trap, do_sparc64_fault, do_debug, oops_begin, oops_end, etc
  - Discovered with our dejagnu stress test suite
- Limited pointer operations

Probe Scripting Language

- Awk/C-like scripting language
- Limited number of types:
  - 64-bit numbers, strings, associative arrays, statistics
- Full control structures (conditionals, oops, functions)
- Safety features:
  - Full static type checking, automatic type inference
  - No dynamic memory allocation
  - Bounded execution space and time
  - No assembly or arbitrary C code (except in guru mode)
  - Protected access to $ target” values in kernel space

Dynamic Probing

- Several underlying interfaces for inserting probes
  - Probepoints provide a uniform interface for identifying events of interest
- Synchronous probepoints
  - kprobes, jprobes, kretprobes (dynamic)
  - SystemTap Marks (static)
- Asynchronous events
  - Timers, Performance counters

Static Probing

- Probe point: wherever hooks are compiled in
- Fixed probe handler: collect fixed pool of context data, dump it to buffer; off-line post-processing
- Low cost dormant probes
- Dispatch cost low

Static Instrumentation Markers

- Decoupling probe *point* and *handler*
- To create: place it, name it, parametrize it. That's it:
  `STAP_MARK_NN(context_switch,prev->pid,next->pid);`
- To use from systemtap:
  `probe kernel.mark(“context_switch”) { print($arg1) }`

```
#define STAP_MARK_NN(n,a1,a2) do { \
  static void (*__stap_mark_##n##_NN)(int64_t,int64_t); \
  if (unlikely (__stap_mark_##n##_NN)) \
    (void) (__stap_mark_##n##_NN((a1),(a2))); \
} while (0)
```

Static Instrumentation Markers

- Marker-based top-process listing; placing a marker in a sensitive spot (context switching)

- ```
/*
 * context_switch - switch to the new MM and the new
 * thread's register state.
 */
static inline struct task_struct *
context_switch(struct rq *rq, struct task_struct *prev,
               struct task_struct *next)
{
        struct mm_struct *mm = next->mm;
        struct mm_struct *oldmm = prev->active_mm;

...
        /* Here we just switch the register state and the stack. */
        STAP_MARK_NN(context_switch, prev->pid, next->pid);
        switch_to(prev, next, prev);

        return prev;
}
```
```

Static Instrumentation Markers

- ```
  probe kernel.mark("context_switch") {
    switches ++   # count number of context switches
    now = get_cycles()
    times[$arg1] += now-lasttime  # accumulate cycles spent in process
    execnames[$arg1] = execname() # remember name of pid
    lasttime = now
  }
  probe timer.ms(3000) { # every 3000 ms
    printf ("\n%5s %20s %10s  (%d switches)\n",
            "pid", "execname", "cycles", switches);
    foreach ([pid] in times-) # sort in decreasing order of cycle-count
      printf ("%5d %20s %10d\n", pid, execnames[pid], times[pid]);
    # clear data for next report
    delete times
    switches = 0
  }
  ...
  ```

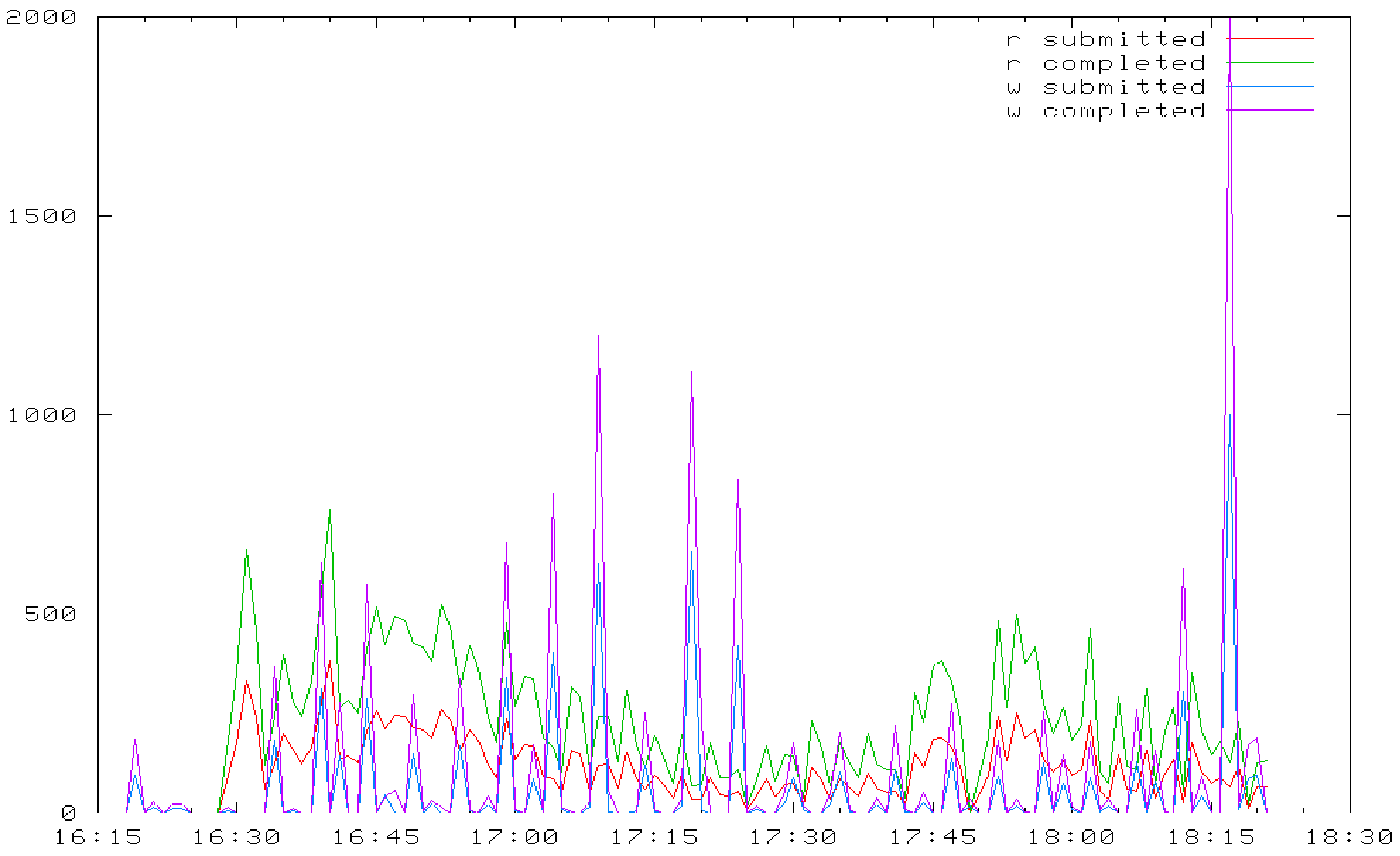
- ```
  # stap mark-top.stp
    pid             execname     cycles  (1813 switches)
      0              swapper  764411819
   4473                    X   51465833
   4538       gnome-terminal   33217978
   4745          firefox-bin   24762308
   ...
  ```

Live Demos

- Which process in the running system uses `open(2)`?
  ```
  int open(const char *pathname, int flags);
  int open(const char *pathname, int flags, mode_t mode);
  ```
- Which system calls are triggered when executing `bash`?
- What programs/scripts are executed when you run a command?
- Which are the top 10 applications that use `sys_ioctl`?
- Use `plimits.stp` to check the rlimits of any arbitrary process
- Use `pfiles.stp` to check the currently opened file descriptors of any arbitrary process
- Use `udpstat.stp` to analyse the UDP traffic in the system
- Hook the `kbd_event` handler to perform something

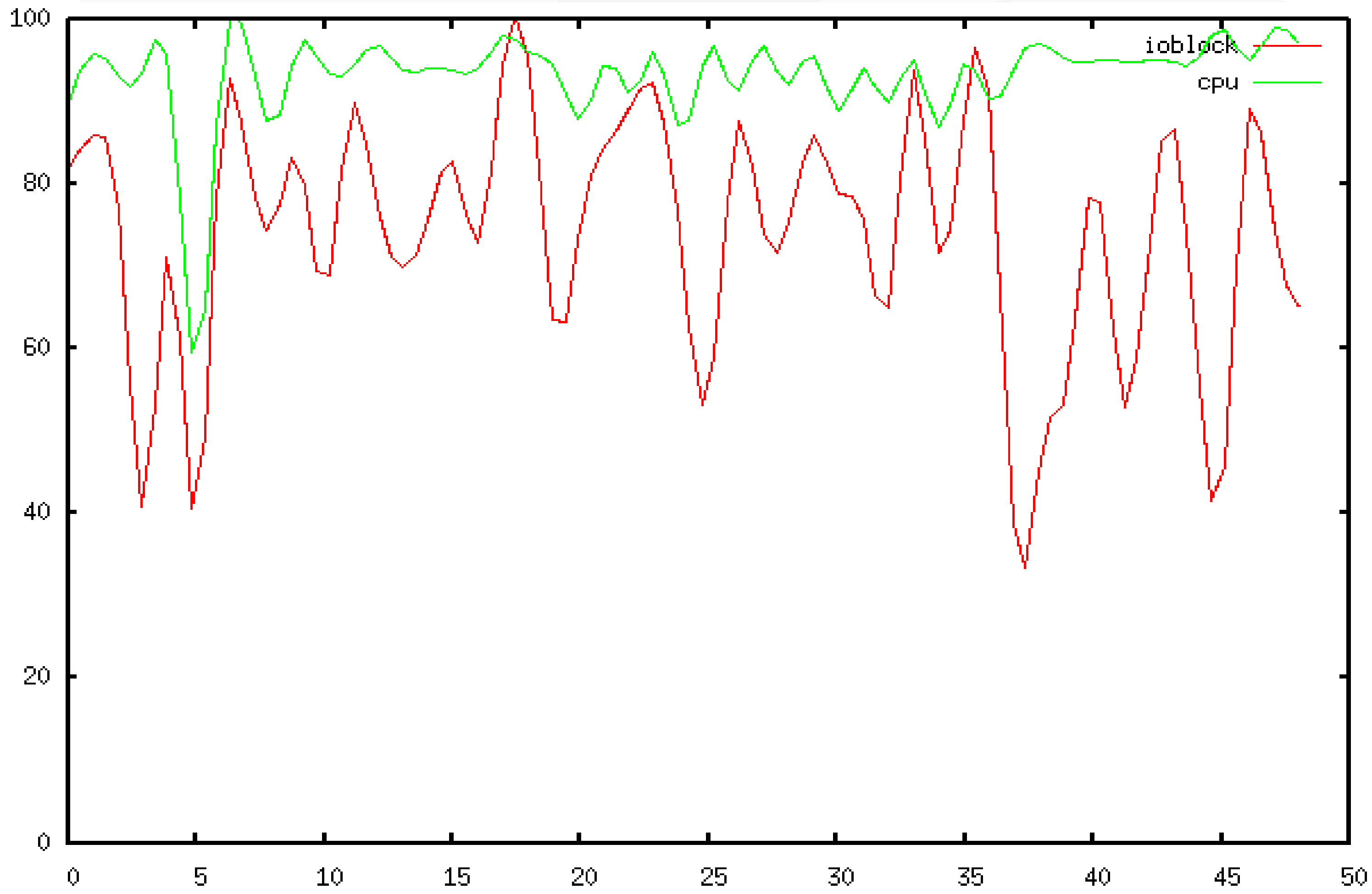
Things that you can write

- Block I/O submissions & completions



Things that you can write

- Is CPU busy now?



SystemTap Demo Scripts

- Scripts demonstrating various SystemTap features can be found at http://sourceware.org/systemtap/documentation.html
  - top.stp - print the top twenty system calls.
  - prof.stp - simple profiling.
  - keyhack.stp - modifying variables in the kernel.
  - kmalloc.stp - statistics example.
  - kmalloc2.stp - example using arrays of statistics.
  - ansi_colors.stp – example using \0?? to display ansi colours
- For example:
  - `$ stap top.stp`

SystemTap Availability

- SystemTap is still evolving rapidly
  - Latest sources available at http://sourceware.org/systemtap
  - Anonymous CVS access
- Distribution & architecture support
  - Red Hat Enterprise Linux 4 from U2 *(technology preview)*
    - x86, EM64T/AMD64, Itanium2
  - Fedora Core 4, 5 & 6
    - x86, EM64T/AMD64, Itanium2, PPC

SystemTap Packages

- Main RPM is `systemtap`
  - `stap, stapd`
  - SystemTap Runtime
  - Tapsets
  - Man pages: `stap(1)`, `stapfuncs(5)`, `stapprobes(5)`, `stapex(5)`
- SystemTap requires
  - `gcc`
  - `kernel-devel`
  - `kernel-debuginfo`

SystemTap Kernel Packages

- SystemTap requires support packages for the kernels in use
- `kernel-devel` RPMs
  - Provide headers, Makefiles and configuration information to allow modules to be built against a packaged kernel
- `kernel-debuginfo` RPMs
  - Provide source and debug symbols for packaged kernels
  - Debug information in DWARF format
    - Allows location of inlines, local variables, macros, line numbers
  - Due to the volume of data kernel-debuginfo RPMs are large
    - But FC6 and RHEL5 will use modular debuginfo packages

War Stories

- We are compiling a list of SystemTap stories, and interesting demos
- If you have a SystemTap success story, do share with us at http://sourceware.org/systemtap/wiki/WarStories

Further Information

- Website: http://sources.redhat.com/systemtap
- Wiki: http://sources.redhat.com/systemtap/wiki
- Mailing list: systemtap@sources.redhat.com
- IRC channel: #systemtap on irc.freenode.net

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