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Dynamic Event Tracing in Linux Kernel

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Who am I?

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- Company
  - Hitachi Data Systems
  - Works at Red Hat office as an on-site engineer
- Linux Kernel
  - Kprobes related matters maintainer
- Systemtap
  - Some enterprise/performance enhancements

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- There are many tracing facilities in kernel today
  - *Ftrace*
  - *Tracepoints*
  - *perf_events*
  - These provide fixed tracing points or hardware events
- Dynamic event tracing has been introduced in 2.6.33
  - A few people knows how to use it.
  - This slide will explain it.

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- Fixed Events
  - Tracepoints - Static event tracing
  - Mcount - Function entry(exit) tracing
- Hardware Events
  - Performance counters - HW event tracing
  - HW Breakpoint - HW memory access tracing
- Dynamic Events
  - **Kprobes - Dynamic event tracing in kernel**
    - What's dynamic? - trace events in the function body
  - Uprobes - Dynamic event tracing in user space
    - Under development

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- Dynamic event tracer
  - Based on kprobes (kprobe and kretprobe)
  - Add/delete new events on the fly
  - trace-event/perf-event compatible
    - Enable/disable, filter and record by ftrace and perf tools
- Put a new trace-event with register/memory arguments
  - Function entry (symbol) + offset / function return
  - Fetch various registers/memory/symbols
    - Dereferencing(resolving pointer) is also supported

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- Get the latest -tip tree
- Make menuconfig
  - Kernel hacking

    -> Tracers (CONFIG_FTRACE = y)

    -> Enable kprobes-based dynamic events (CONFIG_KPEOBE_EVENT = y)
- Rebuild & install kernel & reboot

- Supported architecture
  - x86/x86-64
  - s390
  - PPC

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- See Documentation/trace/kprobetrace.txt
- Interface
  - **(debugfs)/tracing/kprobe_events**
    - Write event definitions
      - `echo "command" >> tracing/kprobe_events`

        (Note: write without O_APPEND (e.g '>') **clears all existing events**)
    - Read current event definitions
      - `cat tracing/kprobe_events`
  - **(debugfs)/tracing/kprobe_profile**
    - Check the profile of each events (nhits/nmissed)

```
Command)
p[:[GRP/]EVENT] SYMBOL[+offs]|MEMADDR [FETCHARGS]: Set a probe
r[:[GRP/]EVENT] SYMBOL[+0] [FETCHARGS]           : Set a return probe
-:[GRP/]EVENT                                    : Clear a probe
```

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- Event arguments can access registers/memory/stack

```
%REG            : Fetch register REG
@ADDR           : Fetch memory at ADDR (ADDR should be in kernel)
@SYM[+|-offs]   : Fetch memory at SYM +|- offs (SYM should be a data symbol)
$stackN         : Fetch Nth entry of stack (N >= 0)
$stack          : Fetch stack address.
$retval         : Fetch return value.(*)
+|-offs(FETCHARG) : Fetch memory at FETCHARG +|- offs address.(**)
NAME=FETCHARG   : Set NAME as the argument name of FETCHARG.
FETCHARG:TYPE   : Set TYPE as the type of FETCHARG. Currently, basic types
                  (u8/u16/u32/u64/s8/s16/s32/s64) are supported.
```

e.g.
'foo=+10(%bp):u32'
fetch u32 value from the address which bp register value plus 10.

'bar=@tick_usec'
fetch unsigned long value of tick_usec symbol.

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- kprobes now checks instruction boundary.
  - If a probe puts at the middle or end of a instruction, returrn -EILSQ
  - x86: instruction decoder decodes target function(symbol)

x86 insn decoder

- Support both of x86/x86-64
  - Support AVX instructions too
- Easy to maintain: generates attribute maps from x86 opcode map

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- Probe setting and tracing on vfs_read

```
<Analyze Binary>
# grep vfs_read /proc/kallsyms
# objdump -Sd vmlinux --start-address=0x.... | less

<Add Event>
# echo 'p vfs_read+..  %di +0x3c(%di):u32' >> kprobe_events

<Show Event>
# cat events/kprobes/p_vfs_read_../format
# cat kprobe_events

<Trace Event>
# echo 1 > events/kprobes/p_vfs_read_../enable
# cat trace

<Delete Event>
# echo '- p_vfs_read_..' >> kprobe_events
```

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- *Flexible*, *Dynamic*, but **Painful**
  - Probepoint : symbol+offset
    - No source code lines, no inlined functions
    - Objdump helps a bit
  - Argument : registers/memory
    - No local variables
    - Objdump can't help it
  - Users have to disassemble binary and analyze it.

```
$ objdump -Sd kernel/sched.o
...
static void update_min_vruntime(struct cfs_rq *cfs_rq)
{
        u64 vruntime = cfs_rq->min_vruntime;
    44b2:       49 8b 45 20             mov    0x20(%r13),%rax

        if (cfs_rq->curr)
    44b6:       48 85 d2                test   %rdx,%rdx
    44b9:       48 89 c1                mov    %rax,%rcx
...
```

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- Some tools can support source-code level analysis
  - *Debugger(gdb)*
  - *SystemTap*
- Both use **debuginfo**
  - Debuginfo provides the information of probe points and local variables
    - Source code information
    - Variable/Structure type information
- Analyzing debuginfo requires user space helper
  - Perf-tools
    - A tool in kernel tree
    - Synchronously update with kernel

-> **Perf probe subcommand**

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- Dynamic event control helper
  - Add new trace events on kprobe-tracer from source-code level information
    - Find inline functions / function relative lines
    - Find local variable locations/types
  - Delete those trace events by name
  - List all trace events with source lines
  - Help user to find which lines can be probed

    (See tools/perf/Documentation/perf-probe.txt)

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- Probe setting and tracing on vfs_read

```
<Analyze Binary>
 # perf probe --line vfs_read

<Add Event>
 # perf probe --add 'vfs_read file file->f_mode'

<Show Event>
 # perf probe --list
 # perf list

<Trace Event>
 # perf record -e probe:vfs_read -aRf ls -l
 # perf trace

<Delete Event>
 # perf probe --del '*'
```

We don't see any registers/memory address, or byte-offsets!

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- --line shows which source code lines can be probed

```
Syntax)
perf probe --line FUNCTION[:RelNumber[+NumLINES|-EndNumber]]
perf probe --line SOURCE:AbsNumber[+NumLINES|-EndNumber]
```

```
Example)
# perf probe --line vfs_read:0+7
<vfs_read:0>
         ssize_t vfs_read(struct file *file, char __user *buf, size_t
      1  {
                ssize_t ret;

      4         if (!(file->f_mode & FMODE_READ))
                        return -EBADF;
      6         if (!file->f_op || (!file->f_op->read && !file->f_op-
```

Lines start with number can be probed.

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- --add adds a new event

```
# perf probe --add '[EVENT=]PROBE_POINT  [ARG1 ARG2 ...]'
or
# perf probe  '[EVENT=]PROBE_POINT  [ARG1 ARG2 ...]'
```

  - Event name
    - This will be created from the probed function name
  - Probe point
    - Function or File and Line number. Lazy matching is also supported
  - Argument
    - Function local variables
    - Kprobe-tracer syntax is also supported

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- Probe point specifies where new event happens

```
Syntax)
[EVENT=]FUNC[@SRC][+Offset|%return|:RelNumber|;Pattern]
or
[EVENT=]SOURCE:AbsNumber|SOURCE;Pattern
```

  - Function name base
    - Support inline function
    - Function relative offset / line-number
    - Support function exit (%return)
      - Note that this is only for non-inlined functions
  - Source file base
    - Tail matching: “sched.c” matches “.../kernel/sched.c”
  - Lazy matching
    - Source line pattern can be specified

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- Lazy matching
  - Put events on every line which matches with the pattern
  - Lazy pattern likes a glob('*','?','[]'), but ignores spaces

```
e.g.
# perf probe --add 'schedule;cpu=*'
  ...
# perf probe --list
  probe:schedule       (on schedule:9@linux-2.6-tip/kernel/sched.c)
  probe:schedule_1     (on schedule:55@linux-2.6-tip/kernel/sched.c)
# perf probe --line schedule
    [...]
      9         cpu = smp_processor_id();
    [...]
    55                cpu = smp_processor_id();
```

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- Arguments of events
  - Local variables are translated by using debuginfo
    - Data structure is going to be available
  - Name is set from the variable name
    - Data structure members has another rule – last field name
  - Type casting is going to be supported (u8/16/32/64, s8/16/32/64)

e.g.
'count'
Get a local variable named 'count' (argument name is 'count')

'file->f_mode'
Get 'f_mode' member of 'file' local variable as '**f_mode**' argument.

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- --list shows current events with source code line numbers
  - Note: arguments are shown by name

```
e.g.
# perf probe --list
  probe:schedule       (on schedule:36@linux-2.6-tip/kernel/sched.c with rq)
  probe:vfs_read       (on vfs_read@linux-2.6-tip/fs/read_write.c with file)
```

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- --del deletes events matching a given glob pattern
- glob expression can be used in other commands (e.g. perf-record)

```
e.g.
# perf probe --del 'schedule*'

Remove dynamic events which name start with 'schedule'

# perf probe --del '*'

Remove ALL dynamic events.
```

- --force
  - Forcibly add new events on the function in where there are already other events
  - Event name will be “function_N” (N is an index)
- --dry-run
  - Don't change kprobe-tracer
  - Only --add/--del are affected
- --verbose
  - Show more messages

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- **Don't Forget you're on the command-line!**
  - Special characters can be translated by shell
    - Kprobe-tracer syntax includes '**$**'
    - Perf probe syntax includes '**;**' '**>**' '*****'
  - Using ' (single-quote) is recommended
- **Test before executing**
  - -fnv (force, dry-run, verbose) is recommend

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- Kernel built options
  - Enabling dynamic perf/trace event
    - CONFIG_KPROBE_EVENT
    - CONFIG_PERF_EVENT
  - Building kernel with debuginfo
    - CONFIG_DEBUG_INFO
      - Will get a bigger binary ... don't upset :)
- Elfutils(Libdw)
  - Dwarf format (debuginfo) analysis library
    - Developed closely with GCC.
  - Without elfutils, perf probe can't support debuginfo
- Architecture
  - x86/x86-64
  - PPC is proposed.

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- Opened TODOs
  - String type support
    - String allows us to trace pathname etc
  - Module support
    - Kernel modules are not supported yet
    - Modules can be relocatable
  - Dynamic indexed array
    - array[i] is commonly used in loops
  - %next
    - Probe the next step line, or just use post_handler

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- 2.6.33
  - Kprobe-tracer
  - Perf probe: prototype feature
  - Note: Requires *libdwarf*
- 2.6.34 (expecting)
  - Adding --line/lazy matching support
  - Note: Move onto *elfutils* (from libdwarf)
    - Elfutils works better with newer gcc
  - **Jump optimized kprobes**
- -tip (ongoing)
  - Data structure member support
  - Type support

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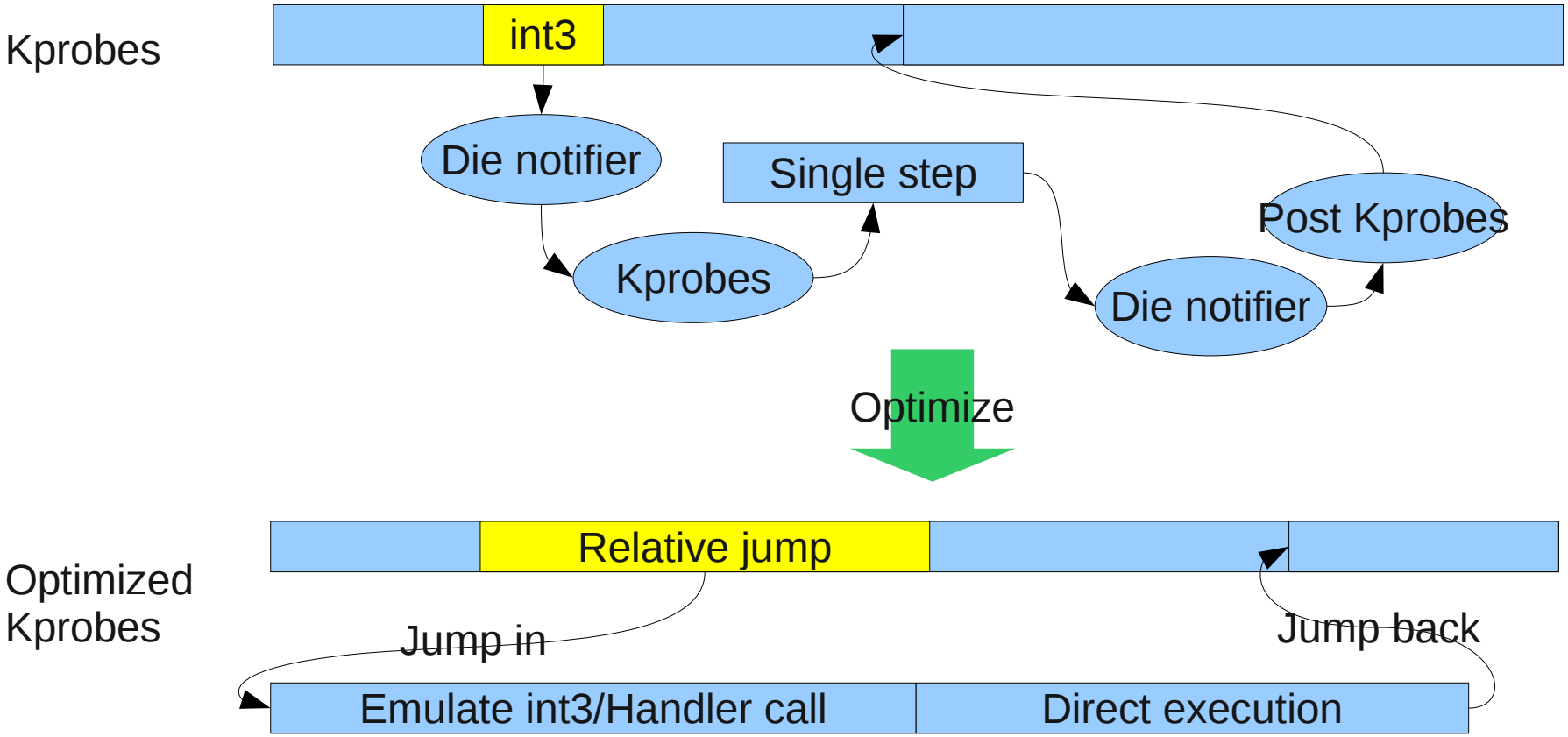
- Kprobes enhancement feature by replacing a breakpoint with a jump instruction.



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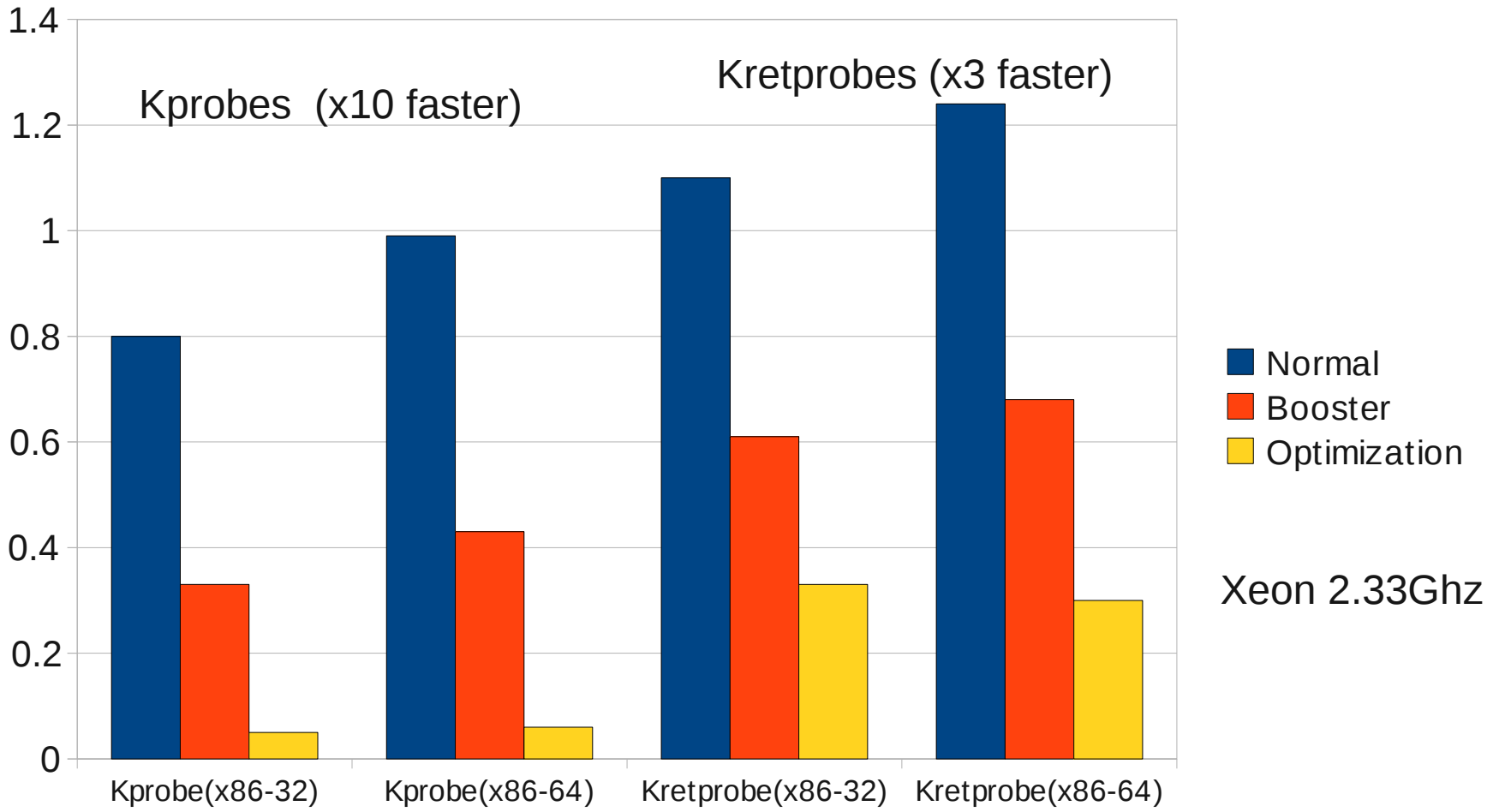
- Overheads/probe (usec) : smaller is better



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- Optimization is **transparently** done
  - **Don't require any user-side changes**
  - No kABI change
    - Just add a flag bit on internal kprobe->flags
  - Not all probes are optimized
- Sysctl interface
  - Disabling/Enabling optimization via sysctl “debug.kprobes-optimization”
    - Enabling(default): debug.kprobes-optimization = 1
    - Disabling: debug.kprobes-optimization = 0

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- Dynamic event tracing
  - In-kernel flexible probe framework
  - Events can trace registers/memory
  - Safety checks can check the instruction boundary
- Perf probe
  - Debuginfo analyzer for helping dynamic event setting from source code info
  - User friendly interface for dynamic event tracing
  - In kernel tree tool
- Kprobe jump optimization
  - Reduce kprobe's overhead drastically
  - No user change: Transparently optimized

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- LWN.net
  - Dynamic probes with ftrace (kprobe-tracer)
    - http://lwn.net/Articles/343766/
  - Minimizing instrumentation impacts (kprobes jump optimization)
    - http://lwn.net/Articles/365833/

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Thank You

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Questions/Discussion

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