How to design a Linux kernel interface

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18 August 2015
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Who am I?

- Maintainer of Linux *man-pages* project since 2004
  - Documents kernel-user-space and C library APIs
  - 15k commits, 168 releases, author/co-author of 350+ of 990+ pages in project
- Quite a bit of design review of Linux APIs
- Lots of testing, lots of bug reports
- Author of a book on the Linux programming interface
- IOW: looking at Linux APIs a lot and for a long time
Theme is more about process than technical detail
1 The problem
2 Think outside your use case
3 Unit tests
4 Specification
5 The problem of the feedback loop
6 Write a real application
7 A technical checklist
8 Doing it right
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Implementation of APIs is the lesser problem

(Performance can be improved later; bugs are irritating, but can be fixed)
API design is the big problem
Why is API design a problem?

- Hard to get right
- (Usually) can’t be fixed
  - Fix == ABI change
  - User-space will break

And...
Thousands of user-space programmers will live with your (bad) design for decades
Many kinds of APIs

- Pseudo-filesystems (/proc, /sys, /dev/mqueue, debugfs, configfs, etc.)
- Netlink
- Auxiliary vector
- Virtual devices
- Signals
- System calls $\Leftarrow$ focus, for purposes of example
- $\text{ioctl()}$, $\text{prctl()}$, $\text{fcntl()}$, and other multiplexor syscalls
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Example: POSIX messages

- POSIX MQs: message-based IPC mechanism, with priorities for messages
  - `mq_open()`, `mq_send()`, `mq_receive()`, ...
  - Linux 2.6.6
- Usual use case: reader consumes messages (nearly) immediately
  - (i.e., queue is usually short)
- Kernel developers coded for usual use case
Example: POSIX messages

- Linux 3.5: a vendor developer raises ceiling on number of messages allowed in MQ
  - Raised from 32,768 to 65,536 to serve a customer request
- I.e., customer wants to queue masses of unread messages
- Developer notices problems with algorithm that sorts messages by priority
  - Approximates to bubble sort(!)
    - Will not scale well with (say) 50k messages in queue...
- Among a raft of other MQ changes, developer fixes sort algorithm
When designing APIs, remember:

User-space programmers are endlessly inventive.
Moral 1: try to imagine the ways in which an army of inventive user-space programmers might (ab)use your API
Is this such a big deal?

A performance bug got found and fixed. So what?

(but there’s more...)
3.5 MQ changes also broke user space in at least two places

- Introduced hard limit of 1024 on `queues_max`, disallowing even superuser to override
  - Fixed by commit f3713fd9c in Linux 3.14, and in -stable
- Semantics of value exported in `/dev/mqueue QSIZE field changed`
  - Now includes overhead bytes
  - http://thread.gmane.org/gmane.linux.man/7050
Moral 2: without unit tests you will screw up someone’s API
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Unit tests

- To state the obvious, unit tests:
  - Prevent behavior regressions in face of future refactoring of implementation
  - Provide checks that API works as expected/advertised
Regressions happen more often than you’d expect
Examples of regressions

- Linux 2.6.12 silently changed meaning of `fcntl()` F_SETOWN
  - No longer possible to target signals at specific thread in multithreaded process
  - Change discovered many releases later; too late to fix
    - Maybe some new applications depend on new behavior!
  - ⇒ Since Linux 2.6.32, we have F_SETOWN_EX to get old semantics

- Inotify IN_ONESHOT flag
  - (inotify == filesystem event notification API added in Linux 2.6.13)
  - By design, IN_ONESHOT did not cause an IN_IGNORED event when watch is dropped after one event
  - Inotify code was refactored during fanotify implementation (early 2.6.30’s)
  - From 2.6.36, IN_ONESHOT does cause IN_IGNORED
Does it do what it says on the tin?

(Too often, the answer is no)
Does it do what it says on the tin?

- **Inotify** `IN_ONESHOT` flag
  - Provide **one** notification event for a monitored object, then disable monitoring
  - Tested in 2.6.16; simply did not work
    - ⇒ zero testing before release...

- **Inotify event coalescing**
  - Successive identical events (same event type on same file) are combined
    - Saves queue space
  - Before Linux 2.6.25, a new event would be coalesced with item at *front* of queue
    - I.e., with oldest event rather than most recent event
    - Clearly: minimal pre-release testing
Does it do what it says on the tin?

- `recvmsg()` *timeout* argument
  - Syscall to receive multiple datagrams, added in 2.6.33
  - *timeout* added late in implementation, after reviewer suggestion

Intention versus implementation:

- Apparent concept: place timeout on receipt of complete set of datagrams
- Actual implementation: timeout *tested only after receipt of each datagram*
  - Renders timeout useless...

Clearly, no serious testing of implementation

- Also, confused implementation with respect to use of `EINTR` error after interruption by signal handler
  - [http://thread.gmane.org/gmane.linux.kernel/1711197/focus=6435](http://thread.gmane.org/gmane.linux.kernel/1711197/focus=6435)
Probably, all of these problems could have been avoided if there were unit tests
Writing a new kernel-user-space API? ⇒ include unit tests

Refactoring code under existing API that has no unit tests? ⇒ please write some
Where to put your tests?

- Historically, only real home was LTP (Linux Test Project), but:
  - Tests were out of kernel tree
  - Often only added after APIs were released
  - Coverage was only partial
- *kselftest* project (started in 2014) seems to be improving matters:
  - Tests reside in kernel source tree
  - Paid maintainer: Shuah Khan
  - Wiki: [https://kselftest.wiki.kernel.org/](https://kselftest.wiki.kernel.org/)
  - Mailing list: *linux-api@vger.kernel.org*
But, how do you know what to test if there is no specification?
Outline

1 The problem
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4 **Specification**
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“Programming is not just an act of telling a computer what to do: it is also an act of telling other programmers what you wished the computer to do. Both are important, and the latter deserves care.”

Andrew Morton, March 2012
Fundamental problem behind (e.g.) `recvmsg()` *timeout* bugs:

no one wrote a specification during development or review
A test needs a specification

*recvmsg()* `timeout` argument needed a specification; something like:

- The `timeout` argument implements three cases:
  1. `timeout` is `NULL`: the call blocks until `vlen` datagrams are received.
  2. `timeout` points to `{0, 0}`: the call (immediately) returns up to `vlen` datagrams if they are available. If no datagrams are available, the call returns immediately, with the error `EAGAIN`.
  3. `timeout` points to a structure in which at least one of the fields is nonzero. The call blocks until either:
     - (a) the specified timeout expires
     - (b) `vlen` messages are received

  In case (a), if one or more messages has been received, the call returns the number of messages received; otherwise, if no messages were received, the call fails with the error `EAGAIN`.

- If, while blocking, the call is interrupted by a signal handler, then:
  - if 1 or more datagrams have been received, then those datagrams are returned (and interruption by a signal handler is not (directly) reported by this or any subsequent call to *recvmsg()*.
  - if no datagrams have so far been received, then the call fails with the error `EINTR`.
Specifications help

Specifications have numerous benefits:

- Provides target for implementer
- Without specification, how can we differentiate implementer’s *intention* from actual *implementation*?
  - IOW: how do we know what is a bug?
- Allow us to write unit tests
- Allow reviewers to more easily understand and critique API
  - ⇒ will likely increase number of reviewers
Where to put your specification?

- At a minimum: in the commit message
- To gain good karma: a *man-pages* patch
Man pages as a test specification

A well written man page often suffices as a test specification for finding real bugs:

- **utimensat()**:

- **timerfd**:
  http://thread.gmane.org/gmane.linux.kernel/613442
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The problem

- Probably 6+ months before your API appears in distributions and starts getting used in real world
- Worst case: only then will bugs be reported and design faults become clear
- But that’s too late...
  - (Probably can’t change ABI...)
- Need as much feedback as possible before API is released
Strive to shorten worst-case feedback loop

⇒

Publicize API design as widely + early as possible
Shortening the feedback loop

Ideally, do all of the following before API release:

- Write a detailed **specification**
- Write **example programs** that fully demonstrate API
- Email relevant mailing lists and, especially, relevant people
- CC **linux-api@vger.kernel.org**
  - Alerts interested parties of API changes:
    - C library projects, *man-pages*, LTP, trinity, kselftest, LSB, tracing projects, and user-space programmers
- For good karma + more publicity: write an LWN.net article
  - Good way of **reaching end users** of your API
    - Ask readers for feedback
  - [http://lwn.net/op/AuthorGuide.lwn](http://lwn.net/op/AuthorGuide.lwn)
Of course, you’d only do all of this if you wanted review and cared about long-term health of the API, right?

- My inner cynic: in some case implementers actively avoid these steps, to minimize patch resistance

- Subsystem maintainers: watch out for developers who avoid these steps
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Example: inotify

- Filesystem event notification API
  - Detect file opens, closes, writes, renames, deletions, etc.
- A Good Thing™ ... 
  - Improves on predecessor (dnotify)
  - Better than polling filesystems using readdir() and stat()
- But it should have been A Better Thing™
Writing a “real” inotify application

- Back story: I thought I understood inotify
- Then I tried to write a “real” application...
  - Mirror state of a directory tree in application data structure
  - 1500 lines of C with (lots of) comments
  - Written up on LWN (https://lwn.net/Articles/605128/)
- And understood all the work that inotify still leaves you to do
- And what inotify could perhaps have done better
The limitations of inotify

Two among several tricky problems when using inotify:

- Event notifications don’t include PID or UID
  - Can’t determine who/what triggered event
  - It might even be you
  - *Why not supply PID / UID, at least for privileged programs?*
- Monitoring of directories is not recursive
  - Must add new watches for each subdirectory
    - (Probably unavoidable limitation of API)
  - Can be expensive for large directory tree ⇒ see next point
The limitations of inotify

File renames generate `MOVED_FROM+MOVED_TO` event pair
- Useful: provides old and new name
- But:
  - Items are not guaranteed to be consecutive
  - No `MOVED_TO` if target directory is not monitored
  - \( \Rightarrow \) matching `MOVED_FROM+MOVED_TO` pairs must be done heuristically and is unavoidably racey
  - Matching failures \( \Rightarrow \) treated as tree delete + tree re-create (expensive!)

*User-space handling would have been much simpler, and deterministic, if `MOVED_FROM+MOVED_TO` had been guaranteed consecutive by kernel*
Only way to discover design problems in a new nontrivial API is by writing complete, real-world application(s) (before the API is released in mainline kernel...)

API limitations should be rectified, or at least clearly documented, before API release...
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A few technical points that frequently come up in Linux API design
New system calls should allow for extensibility

- Allow for future extensibility
- Possibility 1: *flags* bit-mask argument
  - Examples of past failures, and their fixes:
    - `futimesat() \Rightarrow utimensat()`
    - `epoll_create() \Rightarrow epoll_create1()`
    - `renameat() \Rightarrow renameat2()`

  - And many more

    - https://lwn.net/Articles/585415/

- Possibility 2: package arguments in extensible structure
  - Additional *size* argument allows kernel to determine "version" of structure
  - Documentation/adding-syscalls.txt (since Linux 4.2)
APIs should ensure that reserved/unused arguments and undefined bit flags are zero

- EINVAL error
- Allows user-space to test if feature is supported

Failing to do this, allows applications to pass random values to args/masks

- Many historical syscalls failed to do this check

Those applications may fail when future kernels define meanings for those arguments/bits

Conversely: you may not be able to define meanings, because user-space gets broken

- (This has happened)
- https://lwn.net/Articles/588444/
File descriptors syscall should support O_CLOEXEC

- Causes file descriptor (privileged resource) to be closed during `exec()` of new program
- Historical pattern

```c
fd = open(pathname, ...);
flags = fcntl(fd, F_GETFD);
flags |= O_CLOEXEC;
fcntl(fd, F_SETFD, flags);
```

- Multithreaded programs have a race...
  - If another thread does `fork() + exec()` in middle of above steps, FD leaks to new program
- 2.6.27, + 2.6.28 added raft of replacements for existing syscalls to allow O_CLOEXEC to be set at FD creation time
  - E.g., `epoll_create1()`, `inotify_init1()`, `dup3()`, `pipe2()`
- New system calls that create FDs should support O_CLOEXEC
Syscalls with timeouts should allow absolute timeouts

- Some blocking system calls allow setting of timeout to limit blocking period
- In many cases, syscalls support relative timeouts
  - Specify timeout relative to present time (e.g., wait up to 10s)
  - Simple and convenient, often what we want
- But... subject to creep on restart after interruption by signal handler
  - (Because each restart can oversleep)
- ⇒ also include support for absolute timeouts measured on CLOCK_MONOTONIC clock
  - E.g., `clock_nanosleep()` with TIMER_ABSTIME flag
    - (Added precisely to fix creeping sleep problem of `nanosleep()`)

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Designing a Linux kernel interface
Avoid extending multiplexor system calls

- Disfavor adding new commands to existing multiplexor syscalls
  - `prctl()`, `fcntl()`, `ioctl()`
- No type checking of arguments
- Becomes messy when you later decide to extend feature with new options
Capabilities

- General concept:
  - Divide power of root into small pieces
  - Replace set-UID-root programs with programs that have capabilities attached
  - Less harm can be inflicted if program is compromised
- The problem for kernel developers: what capability should I use for my new privileged operation?
  - Read `capabilities(7)`
  - Choose a capability that governs similar operations
  - Or, if necessary, devise a new capability
  - Don’t choose `CAP_SYS_ADMIN`
    - “The new root”
    - 1/3 of all capability checks in kernel are `CAP_SYS_ADMIN`
    - https://lwn.net/Articles/486306/
  - Send in a `man-pages` patch for `capabilities(7)`
64-bit arguments and structure fields

- Take care when dealing with 64-bit arguments and structure fields
  - Jake Edge, “System calls and 64-bit architectures” http://lwn.net/Articles/311630/
“show me a newly released kernel interface, and I’ll show you a bug”

Yes, bugs are fixable, but...

Bug fixes are ABI changes

- Special case: cost of keeping broken ABI > cost of breaking existing ABI
- (Fixed) bad bugs may require user-space to special-case based on kernel version
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Jeff Layton, OFD locks, Linux 3.15 (commit 5d50fffd7c31):

- “Open file description locks” (originally: “file-private locks’’)
- Fix serious design problems with POSIX record locks
  - (POSIX record locks are essentially useless in the presence of any library that works with files)
- Did everything nearly perfectly, in terms of developing feature
Jeff Layton, OFD locks, Linux 3.15 (commit 5d50fffd7c31):

- Clearly explained *rationale* and changes in commit message
- Provided example programs
- Publicized the API
  - Mailing lists
  - LWN.net article (http://lwn.net/Articles/586904/)
- Wrote a man pages patch
  - (Feedback led to renaming of constants and feature)
- Engaged with glibc developers (patches for glibc headers + manual)
  - Refined patches in face of review
  - Maintainers were unresponsive ⇒ resubmitted *many* times
- Made it all look simple
Thanks!

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Slides at http://man7.org/conf/

Linux/UNIX system programming training (and more)
http://man7.org/training/