Why kernel space sucks

(Or: *An abridged history of kernel-userspace interface blunders...*)

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Michael Kerrisk
© 2012
http://man7.org/
mtk@man7.org
mtk@lwn.net

Who am I?

- Professionally: programmer (primarily); also educator and writer
- Working with UNIX + Linux since 1987
- Linux *man-pages* maintainer since 2004
  - 124 releases (as at Aug 2012)
  - written or cowritten ~295 of ~950 man pages
  - lots of API review and testing, many bug reports
- Author of a book on kernel-userspace API
- IOW: **Lots** of time looking at the interface

Intro: Why Userspace Sucks

- Paper/talk by Dave Jones of Red Hat
  - First presented at Ottawa LS 2006
- A lead-in to deconstructing a couple of myths
- *Why Userspace Sucks* → WUSS
  - http://www.kernel.org/doc/ols/2006/ols2006v1-pages-441-450.pdf
  - http://www.codemonkey.org.uk/projects/talks/ols2k6.tar.gz
  - http://lwn.net/Articles/192214/

Motivation for WUSS

- We (kernel developers) have created a kernel that performs magnificently
- But, can we make it better?
  - Why does it take so long to boot, start applications, and shut down?
  - Why does my idle laptop consume so much battery power?

Findings from WUSS

- DJ starts instrumenting the kernel, and finds...
  - Boot up: 80k *stat()*, 27k *open()*, 1.4k *exec()*
  - Shutdown: 23k *stat()*, 9k *open()*
- Userspace programmers wreck performance doing ***crazy*** things!
  - *open()* and reparse same file multiple times!
  - read config files for **many** devices not even present!
  - *stat()* (or even *open()*) 100s of files they never need
  - timers triggering regular unnecessary wake-ups

Conclusions from WUSS

- Room for a lot of improvement in userspace!
- Userspace programmers should be aware of and using trace and analysis tools
  - (perf, LTTng, ftrace, systemtap, strace, valgrind, PowerTOP, etc.)

Kernelspace

Userspace

“We (kernel developers) are much smarter than those crazy userspace programmers”

Kernelspace

Userspace

Something's wrong with this picture...

Let's question a couple of myths...

- **Myth 1**: Kernel programmers (can) always get things right (in the end)
- **Myth 2**: Code is always the best way to contribute to Free Software

Terms: API versus ABI

- **API** == Application **Programming** Interface
- **ABI** == Application **Binary** Interface
  - Conventions used for communicating between two binaries; for example:
    - size of arguments (in bytes),
    - meanings of numeric value of args
- **API → [compilation] → ABI**
- **ABI compatibility** == compatibility of **compiled** binaries
  - Changing ABI affects ***existing*** compiled binaries

Myth 1

Kernel programmers
(can) always get things right
(in the end)

Except, there's (at least) one place where they don't: the interface

The kernel-userspace interface

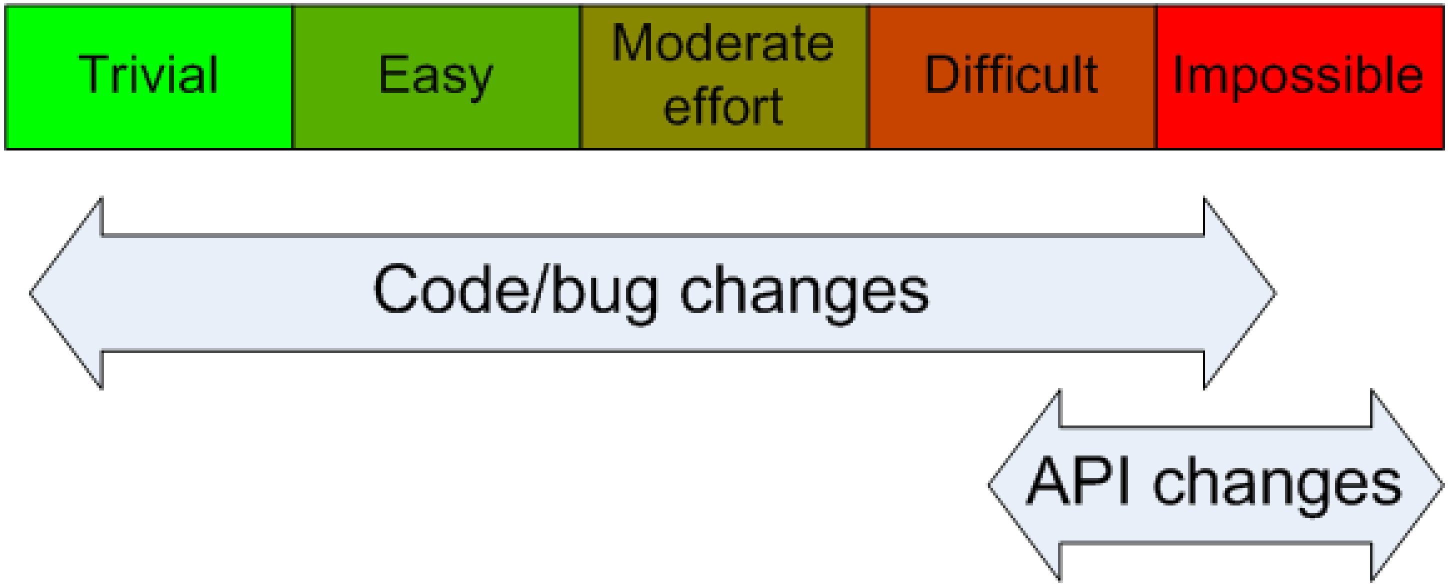
- Application programming interface (API) presented by kernel to userspace programs
    - System calls (← I'll focus here)
    - Pseudo-file systems (/proc, /sys, etc.)
    - *ioctl()* interfaces (device drivers)
    - Netlink sockets
    - Obscure pieces (AUXV, VDSO, ...)

Interface designs must be done

right first time

Why must interfaces be right first time?

- Code changes != API changes



Trivial

Easy

Moderate effort

Difficult

Impossible

Code/bug changes

API changes

Why is fixing interfaces so hard?

- Usually, “fixing” an interface means ***breaking*** the **ABI** for existing binaries

*“Dammit, I'm continually surprised by the *idiots* out there that don't understand that binary compatibility is one of the absolute top priorities.* ***The *only* reason for an OS kernel existing in the first place is to serve user-space.*** *The kernel has no relevance on its own.” [LKML, Mar 2012]*

We have to live with our mistakes!

An interface design mistake by one kernel developer creates pain that ***thousands*** *of userspace programmers must live with for* ***decades***

(In truth, there are shades of gray)

- 100% strict interpretation of ABI compatibility ==> ***never*** change ABI, not even to fix bugs (no matter how bad)
- In truth, ABI breakages are weighed against factors such as:
  - How important is it to make a bug fix?
  - How likely is existing userspace to be affected by ABI change, and how much pain will be caused?
    - e.g., if interface is new, has very specialized uses, or has very few users, then maybe it could be changed

So, what does it mean to get an API right?

Doing (kernel-userspace) APIs right

- Properly designed and implemented API should:
  - be bug free!
  - have a well thought out design
    - simple as possible (but no simpler)
    - easy to use / difficult to misuse
  - be consistent with related/similar APIs
  - integrate well with existing APIs
    - e.g., interactions with *fork()*, *exec()*, threads, signals, FDs?
  - be as general as possible
  - be extensible, where needed; accommodate future growth trends
  - adhere to relevant standards (as far as possible) (e.g., POSIX)
  - be as good as, or better than, earlier APIs with similar functionality
  - be maintainable over time (a multilayered question)

So how do kernel developers score?

Bugs

Bugs

- *utimensat(2)* [2.6.22]
  - Set file timestamps
  - Multiple bugs!
    - http://linux-man-pages.blogspot.com/2008/06/whats-wrong-with-kernel-userland_30.html
  - Fixed in 2.6.26
- *signalfd()* [2.6.22]
  - Receive signals via a file descriptor
  - Didn't correctly obtain data sent with *sigqueue(2)*
  - Fixed in 2.6.25

Bugs

- Examples of other interfaces with significant, easy to find bugs at release:
  - *inotify* [2.6.13]
  - *splice()* [2.6.17] (http://marc.info/?l=linux-mm&m=114238448331607&w=2)
  - *timerfd* [2.6.22] (http://marc.info/?l=linux-kernel&m=118517213626087&w=2)

Bugs—what's going on?

- There's a quality control issue; **way too many** bugs in released interfaces
- Pre-release testing insufficient and haphazard:
  - Too few testers (maybe just kernel developer)
  - No unit tests
  - Insufficient test coverage
  - No clear specification against which to test
- Even if bug is fixed, users may still need to care
  - special casing for kernel versions

Thinking about design

Code it now, think about it later

- Vanishing arguments:
  - *readdir(2)* ignores *count*
  - *getcpu(2)* [2.6.19] ignores *tcache*
  - *epoll_create()* [2.6] ignores *size* (must be > 0) since 2.6.8
- Probably, argument wasn't needed to start with
  - Later recognized as a bad idea and made a no-op

Code it now, think about it later

- *futimesat()* [2.6.16]
  - Extends *utimes()*
  - ***Proposed*** for POSIX.1-2008
  - Implemented on Linux
  - POSIX.1 committee realizes API is insufficient
    → standardizes different API
  - *utimensat()* added in Linux 2.6.22

Code it now, think about it later

- Dec 2003: Linux 2.6 added *epoll_wait()*
  - File descriptor monitoring
    - (improves on *select()*)
  - Nov 2006, 2.6.19 added *epoll_pwait()* to allow manipulation of signal mask during call
    - Superset of *epoll_wait()*
  - But, already in 2001, POSIX specified *pselect()* to fix analogous, well-known problem in *select()*

Consistency

Interface inconsistencies

- *mlock(start, length)*:
  - Round *start* down to page size
  - Round *length* up to next page boundary
  - *mlock(4000, 6000)* affects bytes 0..12287
    - (assuming page size is 4096 bytes)
- *remap_file_pages(start, length, ...)* [2.6]:
  - Round *start* down to page boundary
  - Round *length* **down** to page boundary(!)
  - *remap_file_pages(4000, 6000, ...)* ? → **0..4095**
- Users expect similar APIs to behave similarly

Confusing the users

- Various system calls allow one process to change attributes of another process
  - e.g., *setpriority(), ioprio_set(), migrate_pages(), prlimit()*
- **Unprivileged** calls require credential matches:
  - Some combination of caller's UIDs/GIDs matches some combination of target's UIDs/GIDs

Confusing the users

- But, much inconsistency; e.g.:
  - *setpriority(): euid == t-uid || euid == t-euid*
  - *ioprio_set(): uid == t-uid || euid == t-uid*
  - *migrate_pages(): uid == t-uid || uid == t-suid || euid == t-uid || euid == t-suid*
  - *prlimit(): (uid == t-uid && uid == t-euid && uid == t-suid) && (gid == t-gid && gid == t-guid && gid == t-sgid)* **!!!!**
- Inconsistency may confuse users into writing bugs
  - **Potentially, security-related bugs!**
- http://linux-man-pages.blogspot.com/2010/11/system-call-credential-checking-tale-of.html

Generality

Is the interface sufficiently general?

- 2.6.22 added *timerfd(ufd, flags, utimerspec)*
  - Create timer that notifies via a file descriptor
- But API didn't allow user to:
  - Retrieve previous value when setting new timer value
  - Do a “get” to retrieve time until next expiration
    - http://marc.info/?l=linux-kernel&m=118517213626087&w=2
    - http://lwn.net/Articles/245533/
- Older APIs (*[gs]etitimer()*, POSIX timers) ***did*** provide this functionality!

Is the interface sufficiently general?

- Solution:
  - *timerfd()* disabled in kernel 2.6.23
  - 2.6.25 did it right:
    - *timerfd_create()*, *timerfd_settime()*, *timerfd_gettime()*
    - (API analogous to POSIX timers)
- Was an ABI breakage, but
  - Only in a single kernel version
  - Original API was never exposed via *glibc*

Are we learning from the past?

Are we learning from past mistakes?

- Dnotify [2.4]
  - Directory change notification API
  - Many problems
- So, we added inotify [2.6.13]
  - *Much* better, but still has some problems
- Linux 2.6.37 added yet another related API, fanotify
  - Designed for virus scanners
  - Adds some functionality
  - Doesn't provide all functionality of inotify
- Couldn't we have had a new API that did everything?

Extensibility

Is the interface extensible?

- Too often, an early syscall didn't allow for extensions
- Common solution is a *new* syscall, with a *flags* arg:
  - *umount()* → *umount2()* [2.2]
  - *epoll_create()* [2.6] → *epoll_create2()* [2.6.27]
  - *futimesat()* [2.6.16] → *utimensat()* [2.6.22]
  - *signalfd()* [2.6.22] → *signalfd4()* [2.6.27]
- When adding a new syscall, consider adding an (unused) *flags* argument to allow extensions

Futureproofing

- Suppose a syscall has a *flags* bit-mask arg.
- Implementation should always have check like:

```
if (flags & ~(FL_X | FL_Y))
    return -EINVAL;
    // Only allow caller to specify flags
    // bits that have a defined meaning
```

- Without this check, interface is “loose”

Futureproofing

- Suppose user makes a call of form:

```
    syscallxyz(-1);  // flags has all bits set
```

- If implementer later adds `FL_Z`, an ABI breakage occurs for user's code
- Conversely: user has no way of checking if a particular kernel implements `FL_Z`
- Many system calls lack this kind of check!
  - Linux 3.2 examples: *sigaction(sa.sa_flags), recv(), send(), clock_nanosleep(), msgrcv(), msgget(), semget(), shmget(), shmat(), semop(sops.sem_flg)*

Futureproofing

- Should checks be added after the fact?
  - e.g., *umount2()* [2.2] added check in 2.6.34; *timerfd_settime()* [2.6.25] added check in 2.6.29
- But adding check can also create ABI breakage
  - Apps get errors where previously they did not
    - e.g., kernel commit a8159414, *epoll_ctl()*, May 2012
- ***Loose APIs allow the user to define interface***
  - Worst case: can't add new *flags* values to interface

Futureproofing failures

- 16 bits is enough for UIDs/GIDs...
  - 2.4: 32-bit UIDs/GIDs
- 32 bits is enough for file offsets
  - Okay, it was 1991, but Moore's law...
  - 2.4: 64-bit file offsets
- So we have
  - *oldstat()*, *stat()*, *stat64()*
  - *chown()*, *chown32()*
  - *open()*, *open64()*
  - and so on

Maintainability

When good ideas go astray

- Traditional UNIX gives *root* all privileges
  - All or nothing is risky!
- Linux capabilities divide *root* privileges into distinct pieces
  - Trade-off:
    - Want to split *root* into meaningfully separate pieces
    - Too many pieces becomes unmanageable

When good ideas go astray

- Linux 3.2 has 36 capabilities:
  - CAP_AUDIT_CONTROL, CAP_AUDIT_WRITE, CAP_CHOWN, CAP_DAC_OVERRIDE, CAP_DAC_READ_SEARCH, CAP_FOWNER, CAP_FSETID, CAP_IPC_LOCK, CAP_IPC_OWNER, CAP_KILL, CAP_LEASE, CAP_LINUX_IMMUTABLE, CAP_MAC_ADMIN, CAP_MAC_OVERRIDE, CAP_MKNOD, CAP_NET_ADMIN, CAP_NET_BIND_SERVICE, CAP_NET_BROADCAST, CAP_NET_RAW, CAP_SETFCAP, CAP_SETGID, CAP_SETPCAP, CAP_SETUID, CAP_SYSLOG, CAP_SYS_ADMIN, CAP_SYS_BOOT, CAP_SYS_CHROOT, CAP_SYS_MODULE, CAP_SYS_NICE, CAP_SYS_PACCT, CAP_SYS_PTRACE, CAP_SYS_RAWIO, CAP_SYS_RESOURCE, CAP_SYS_TIME, CAP_SYS_TTY_CONFIG, CAP_WAKE_ALARM
- But which capability do I use for my new feature?
- I don't know... maybe `CAP_SYS_ADMIN`?
- `CAP_SYS_ADMIN`, the new root, **451 uses in 3.2**
  - (out of 1167 total uses of `CAP_*`)
    - https://lwn.net/Articles/486306/

Standards and portability

Needlessly breaking portability

- *sched_setscheduler()*
  - POSIX: successful call must return previous policy
  - Linux: successful call returns 0
  - ***No*** good reason for this inconsistency
  - Developers must special case code for Linux

Actually,
it wasn't just us...

We're just traditionalists...

- These kinds of problems predate Linux:
  - Using syscall function result to both return info on success and indicate an error creates problems
    - Some syscalls can return -1 on success (e.g., *getpriority()*)
  - API of System V IPC is awful!
  - Semantics of *fcntl()* locks when FD is closed render locks useless for libraries
  - *select()* modifies FD sets in place, forcing reinitialization inside loops
    - *poll()* gets it right: uses separate input and output args
  - and so on...

Summary?

We could be doing a *lot* better at API design

Why do these API problems keep happening?

- Excessive focus on code as primary contribution of value for a software project
- Poor feedback loop between developers and users

Myth 2

Code is always the best way to contribute to Free Software

“Show me the code!”

But anyone can write code,
and if the design is good
but the code is bad,
the code can usually be fixed

“Show me the code!”

Sometimes,
other sentences are more appropriate,
and encourage contributions that are
as (or more) valuable

“Show me the users' requirements!”

“Show me the users' requirements”

- Does API serve needs of *multiple* users, or is it just one developer scratching an itch?
    - Beware of limited perspectives!
- Is API designed for **generality**?
- Is API **extensible** for possible future requirements?

“Show me the design specification / documentation!”

“Show me the design spec. / documentation!”

- How do we know if implementation deviates from intention?
- What shall we code our tests against?
- Writing documentation turns out often to be a natural sanity check for design
- A decent man page suffices
  - Most of the bugs mentioned earlier were found while writing man pages...
  - Just a question of when man page is written...

“Show me the design spec. / documentation!”

*“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, LKML, Mar 2012]

“Show me the design review!”

“Show me the design review!”

- Did other people actually review your design?
- Is API:
  - as simple as possible?
  - easy to use / difficult to misuse?
  - consistent with related/similar APIs?
  - well integrated with existing APIs?
  - as general as possible
  - extensible?
  - following standards, where relevant?
  - at least as good as earlier APIs with similar functionality?
  - maintainable?

“Show me the tests!”

“Show me the tests!”

- Did you (the developer) write some tests?
- Did **someone else** write some tests?
- Do the tests cover all reasonable cases?
- Do you test for ***unreasonable*** cases?
    - Do unexpected inputs generate suitable error returns?
- While writing tests, did you find the interface easy to use / difficult to misuse?
    - (Did you consequently make some design changes?)

Finally...

- *If you're a potential contributor, don't fall into the trap of believing that code is the only (or best) vehicle for contribution*
- *As a maintainer, are you encouraging these other types of contribution?*

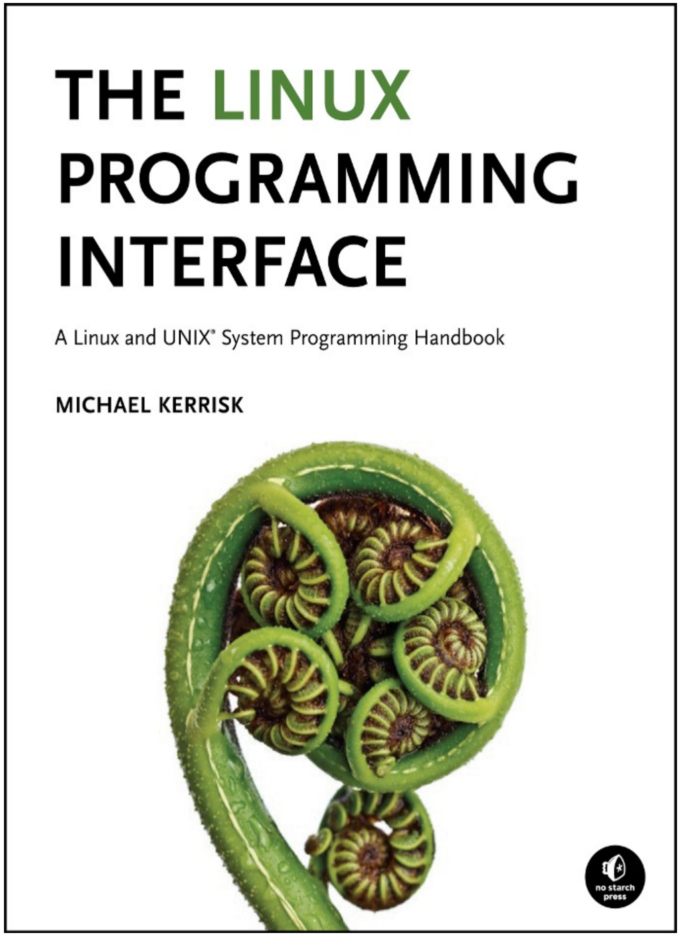
Thanks! And Questions

(slides up soon at http://man7.org/conf/)

Michael Kerrisk
mtk@man7.org
http://man7.org/tlpi

LWN.net
mtk@lwn.net
http://lwn.net/

Linux *man-pages* project
mtk.manpages@gmail.com
http://www.kernel.org/doc/man-pages/


THE LINUX PROGRAMMING INTERFACE
A Linux and UNIX® System Programming Handbook
MICHAEL KERRISK
no starch press

(No Starch Press, 2010)

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