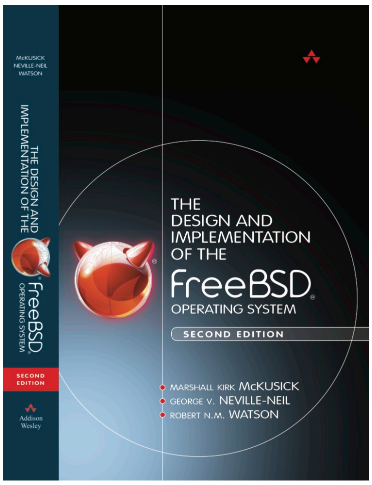
Concurrent systems

Case study: FreeBSD kernel concurrency

Dr Robert N. M. Watson

FreeBSD kernel

- Open-source OS kernel
  - **Large**: millions of LoC
  - **Complex**: thousands of subsystems, drivers, ...
  - **Very concurrent**: dozens or hundreds of CPU cores/threads
  - **Widely used**: NetApp, EMC, Dell, Apple, Juniper, Netflix, Sony, Cisco, Yahoo!, …
- Why a case study?
  - Employs C&DS principles
  - Concurrency performance and composability at scale



In the library: Marshall Kirk McKusick, George V. Neville-Neil, and Robert N. M. Watson. *The Design and Implementation of the FreeBSD Operating System (2nd Edition)*, Pearson Education, 2014.

BSD + FreeBSD: a brief history

- 1980s Berkeley Standard Distribution (BSD)
  - 'BSD'-style open-source license (MIT, ISC, CMU, …)
  - UNIX Fast File System (UFS/FFS), sockets API, DNS, used TCP/IP stack, FTP, sendmail, BIND, cron, vi, …
- Open-source FreeBSD operating system

  1993: FreeBSD 1.0 without support for multiprocessing

  1998: FreeBSD 3.0 with "giant-lock" multiprocessing

  2003: FreeBSD 5.0 with fine-grained locking
  2005: FreeBSD 6.0 with mature fine-grained locking

  2012: FreeBSD 9.0 with TCP scalability beyond 32 cores

3

FreeBSD: before multiprocessing (1)

- Concurrency model inherited from UNIX
- Userspace
  - **Preemptive multitasking** **between** processes
  - Later, **preemptive multithreading** **within** processes
- Kernel
  - 'Just' a C program running 'bare metal'
  - Internally multithreaded
  - User threads 'in kernel' (e.g., in system calls)
  - Kernel services (e.g., async. work for VM, etc.)

4

FreeBSD: before multiprocessing (2)

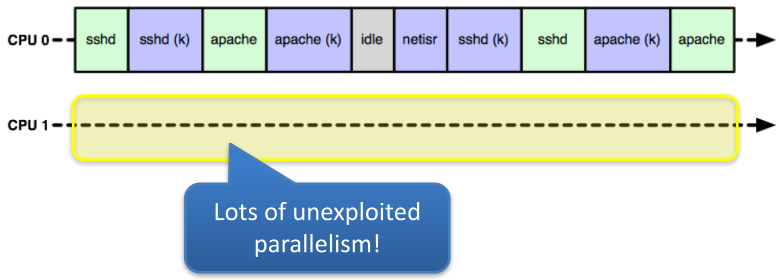
- **Cooperative multitasking** within kernel
  - Mutual exclusion as long as you don't `sleep()`
  - Implied global lock means local locks rarely required Except for interrupt handlers, non-preemptive kernel
  - **Critical sections** control interrupt-handler execution
- **Wait channels**: implied condition variable for every address

```
sleep(&x, …);          // Wait for event on &x
wakeup(&x);            // Signal an event on &x
```

  - Must leave global state consistent when calling `sleep()`
  - Must reload any cached local state after `sleep()` returns
- Use to build higher-level synchronization primitives
  - E.g., `lockmgr()` reader-writer lock can be held over I/O (sleep)

5

Pre-multiprocessor scheduling



6

Hardware parallelism, synchronization

- Late 1990s: multi-CPU begins to move down market
  - In 2000s: 2-processor a big deal
  - In 2010s: 64-core is increasingly common
- **Coherent**, **symmetric**, **shared memory** systems
  - Instructions for **atomic memory access**
    - Compare-and-swap, test-and-set, load linked/store conditional
- Signaling via **Inter-Processor Interrupts** (IPIs)
  - CPUs can trigger an interrupt handler on each another
- Vendor extensions for performance, programmability
  - MIPS inter-thread message passing
  - Intel TM support: TSX (Whoops: HSW136!)

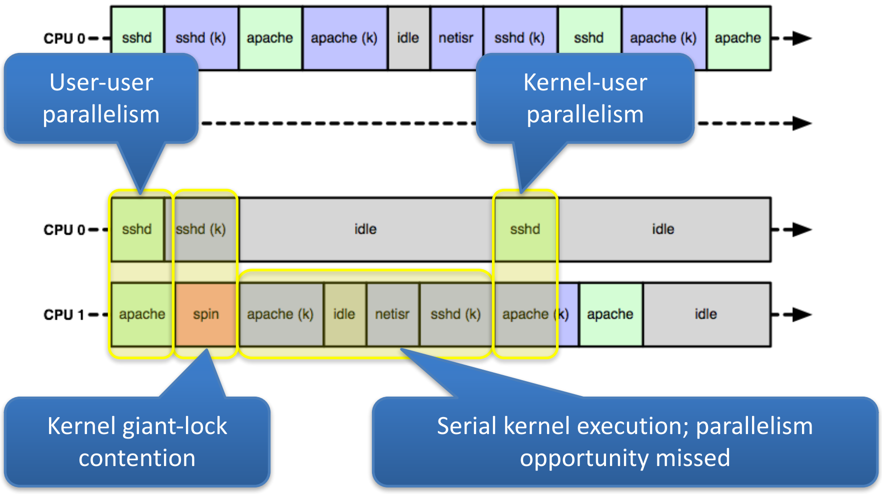
7

Giant locking the kernel

- FreeBSD follows footsteps of Cray, Sun, …
- First, allow user programs to run in parallel
  - One instance of kernel code/data shared by all CPUs
  - Different user processes/threads on different CPUs
- **Giant spinlock** around kernel
  - Acquire on syscall/trap to kernel; drop on return
  - In effect: kernel runs on at most once CPU at a time; ‘migrates’ between CPUs on demand
- **Interrupts**
  - If interrupt delivered on CPU X while kernel is on CPU Y, forward interrupt to Y using an IPI

8

Giant-locked scheduling



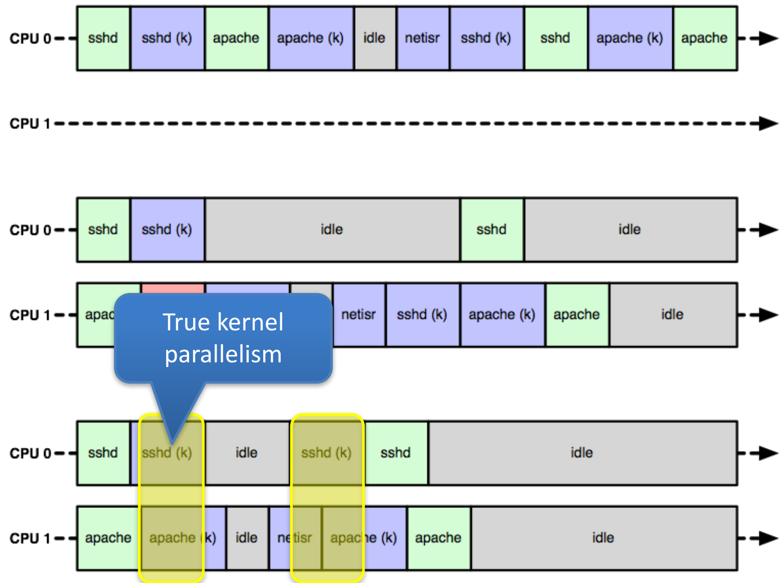
9

Fine-grained locking

- Giant locking is OK for user-program parallelism
- Kernel-centered workloads trigger **Giant contention**
  - Scheduler, IPC-intensive workloads
  - TCP/buffer cache on high-load web servers
  - Process-model contention with multithreading (VM, …)
- Motivates migration to **fine-grained locking**
  - Greater granularity (may) afford greater parallelism
- Mutexes/condition variables rather than semaphores
  - Increasing consensus on pthreads-like synchronization
  - Explicit locks are easier to debug than semaphores
  - Support for **priority inheritance** + **priority propagation**
  - E.g., Linux is also now migrating away from semaphores

10

Fine-grained scheduling



11

Kernel synchronization primitives

- **Spin locks**
  - Used to implement the scheduler, interrupt handlers
- **Mutexes**, **reader-writer**, **read-mostly locks**
  - Most heavily used – different optimization tradeoffs
  - Can be held only over "bounded" computations
  - **Adaptive**: on contention, sleep is expensive; spin first
  - Sleeping depends on scheduler, and hence on spinlocks…
- **Shared-eXclusive (SX) locks**, **condition variables**
  - Can be held over I/O and other unbounded waits
- **Condition variables** usable with any lock type
- Most primitives support **priority propagation**

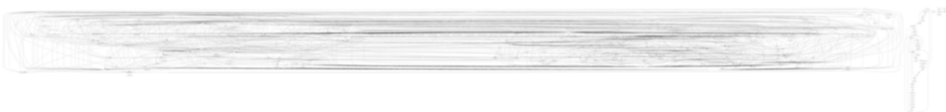
12

WITNESS lock-order checker

- Kernel relies on **partial lock order** to prevent deadlock (Recall dining philosophers)
  - In-field lock-related deadlocks are (very) rare
- WITNESS is a **lock-order debugging tool**
  - Warns when lock cycles (could) arise by tracking edges
  - Only in debugging kernels due to overhead (15%+)
- Tracks both statically declared, dynamic lock orders
  - **Static orders** most commonly intra-module
  - **Dynamic orders** most commonly inter-module
- Deadlocks for condition variables remain hard to debug
  - What thread should have woken up a CV being waited on?
  - Similar to semaphore problem

13

WITNESS: global lock-order graph*



* Turns out that the global lock-order graph is pretty complicated.

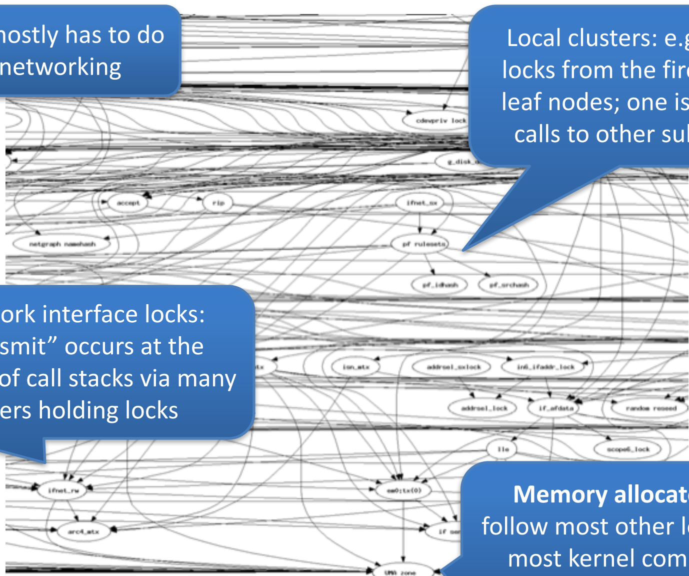
14

*

* Commentary on WITNESS full-system lock-order graph complexity; courtesy Scott Long, Netflix

15

Excerpt from global lock-order graph*



This bit mostly has to do with networking

Local clusters: e.g., related locks from the firewall: two leaf nodes; one is held over calls to other subsystems

Network interface locks: “transmit” occurs at the bottom of call stacks via many layers holding locks

Memory allocator locks follow most other locks, since most kernel components require memory allocation

* The local lock-order graph is **also** complicated.

WITNESS debug output

```
1st 0xffffff80025207f0 run0_node_lock (run0_node_lock) @
/usr/src/sys/net80211/ieee80211_ioctl.c:1341
 2nd 0xffffff80025142a8 run0 (network driver) @
/usr/src/sys/modules/usb/run/../../../dev/usb/wlan/if_run.c:3368

KDB: stack backtrace:
db_trace_self_wrapper() at db_trace_self_wrapper+0x2a
kdb_backtrace() at kdb_backtrace+0x37
_witness_debugger() at _witness_debugger+0x2c
witness_checkorder() at witness_checkorder+0x853
_mtx_lock_flags() at _mtx_lock_flags+0x85
run_raw_xmit() at run_raw_xmit+0x58
ieee80211_send_mgmt() at ieee80211_send_mgmt+0x4d5
domlme() at domlme+0x95
setmlme_common() at setmlme_common+0x2f0
ieee80211_ioctl_setmlme() at ieee80211_ioctl_setmlme+0x7e
ieee80211_ioctl_set80211() at ieee80211_ioctl_set80211+0x46f
in_control() at in_control+0xad
ifioctl() at ifioctl+0xece
kern_ioctl() at kern_ioctl+0xcd
sys_ioctl() at sys_ioctl+0xf0
amd64_syscall() at amd64_syscall+0x380
Xfast_syscall() at Xfast_syscall+0xf7
--- syscall (54, FreeBSD ELF64, sys_ioctl), rip = 0x
0x7fffffffd848, rbp = 0x2a ---
```

Lock names and source code locations of acquisitions adding the offending graph edge

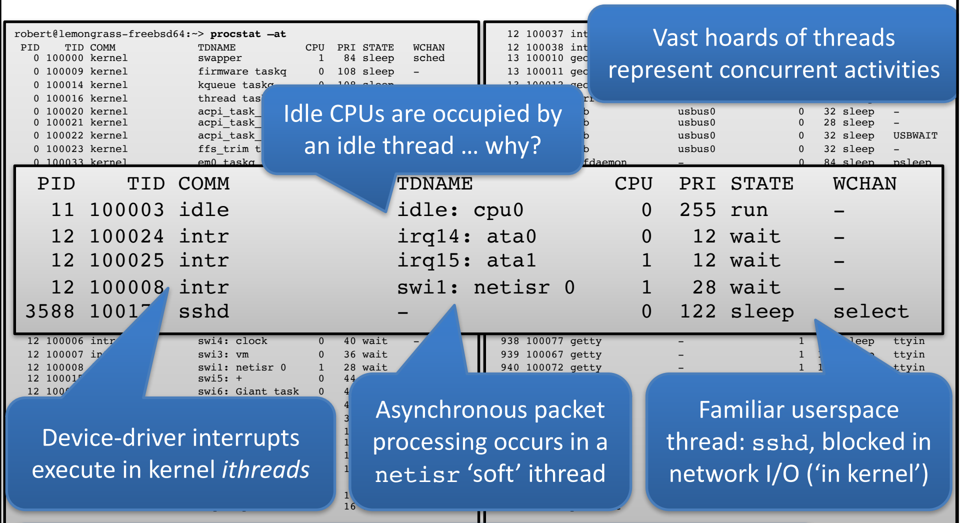
Stack trace to acquisition that triggered cycle: 802.11 called USB; previously, perhaps USB called 802.11?

How does this work in practice?

- Kernel is heavily multi-threaded
- Each user thread has a corresponding kernel thread
  - Represents user thread when in syscall, page fault, etc.
- Kernels services often execute in asynchronous threads
  - Interrupts, timers, I/O, networking, etc.
- Therefore extensive synchronization
  - Locking model is almost always data-oriented
  - Think 'monitors' rather than 'critical sections'
  - Reference counting or reader-writer locks used for stability
  - Higher-level patterns (producer-consumer, active objects, etc.) used frequently

18

Kernel threads in action



Kernel-internal concurrency is represented using a familiar **shared memory threading model**

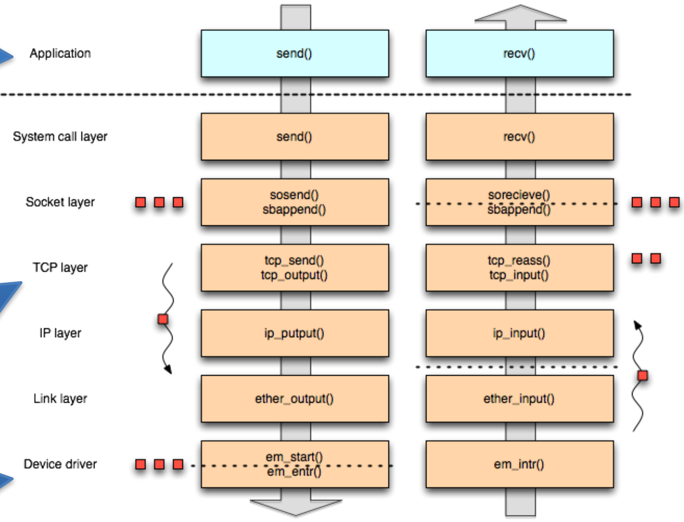
19

Case study: the network stack (1)

- What is a **network stack**?
  - Kernel-resident library of networking routines
  - Sockets, TCP/IP, UDP/IP, Ethernet, …
- Implements user abstractions, network-interface abstraction, protocol state machines, sockets, etc.
  - System calls: socket(), connect(), send(), recv(), listen(), …
- Highly complex and concurrent subsystem
  - Composed from many (pluggable) elements
  - Socket layer, network device drivers, protocols, …
- Typical paths 'up' and 'down': packets come in, go out

20

Network-stack work flows



Applications send, receive, await data on sockets

Data/packets processed; dispatched via **producer-consumer relationships**

Packets go in and out of network interfaces

The work: adding/removing headers, calculating checksums, fragmentation/defragmentation, segment reassembly, reordering, flow control, etc.

Case study: the network stack (2)

- First, make it **safe** without the Giant lock
  - Lots of data structures require locks
  - Condition signaling already exists but will be added to
  - Establish key work flows, lock orders
- Then, make it **fast**
  - Especially locking primitives themselves
  - Increase locking granularity where there is contention
- As hardware becomes more parallel, identify and exploit further concurrency opportunities
  - Add more threads, distribute more work

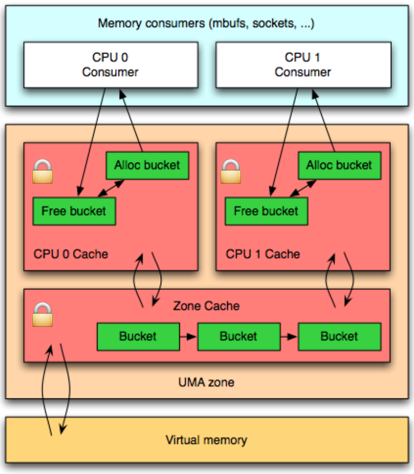
22

What to lock and how?

- Fine-grained locking **overhead** vs. **contention**
  - Some contention is inherent: reflects necessary communication
  - Some contention is **false sharing**: side effect of structure choices
- Principle: lock data, not code (i.e., not critical sections)
  - Key structures: network interfaces, sockets, work queues
  - Independent structure instances often have their own locks
- Horizontal vs. vertical parallelism
  - H: Different locks for different connections (e.g., TCP1 vs. TCP2)
  - H: Different locks within a layer (e.g., receive vs. send buffers)
  - V: Different locks at different layers (e.g., socket vs. TCP state)
- Things not to lock: packets in flight - mbufs ('work')

23

Example: Universal Memory Allocator (UMA)



- Key kernel service
- Slab allocator
  - (Bonwick 1994)
- Per-CPU caches
  - Individually locked
  - Amortise (or avoid) global lock contention
- Some allocation patterns only per-CPU caches
- Others require dipping into the global pool

24

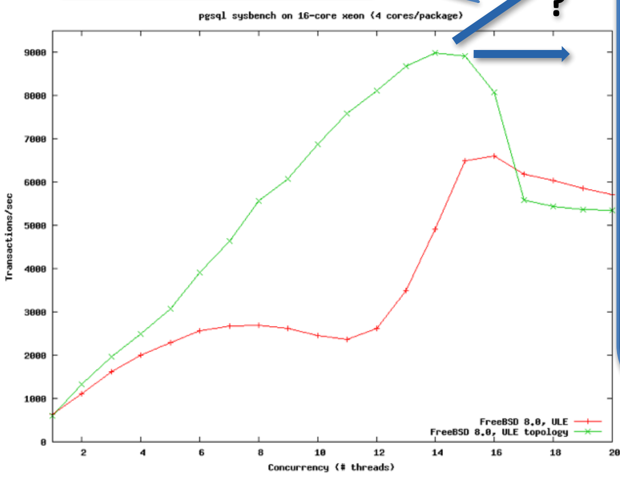
Work distribution

- Packets (mbufs) are units of work
- Parallel work requires distribution to threads
  - Must keep packets ordered – or TCP gets cranky!
- Implication: strong per-flow serialization
  - I.e., no generalized producer-consumer/round robin
  - Various strategies to keep work ordered; e.g.:
    - Process in a single thread
    - Multiple threads in a 'pipeline' linked by a queue
  - Misordering allowed between flows, just not within them
- Establish flow-CPU affinity can both order processing and utilize caches well

Scalability

What might we expect if we didn't hit contention?

?



Key idea:
speedup

As we add more parallelism, we would like the system to get faster.

Key idea:
performance collapse

Sometimes parallelism hurts performance more than it helps due to work-distribution overheads, contention.

Longer-term strategies

- Hardware change motivates continuing work
  - Optimize inevitable contention
  - Lockless primitives
  - rmlocks, read-copy-update (RCU)
  - Per-CPU data structures
  - Distribute work to more threads .. to utilise growing core count
- Optimise for locality, not just contention: cache, NUMA, and I/O affinity

27

Conclusions

- FreeBSD employs many of C&DS techniques
  - Mutual exclusion, condition synchronization
  - Producer-consumer, lockless primitives
  - Also Write-Ahead Logging (WAL) in filesystems
- Real-world systems are really complicated
  - Hopefully, you will mostly consume, rather than produce, concurrency primitives like these
  - Composition is not straightforward
  - Parallelism performance wins are a lot of work
  - Hardware continues to evolve
- See you in Distributed Systems!

28