Concurrent systems

Lecture 8: Case study - FreeBSD kernel concurrency

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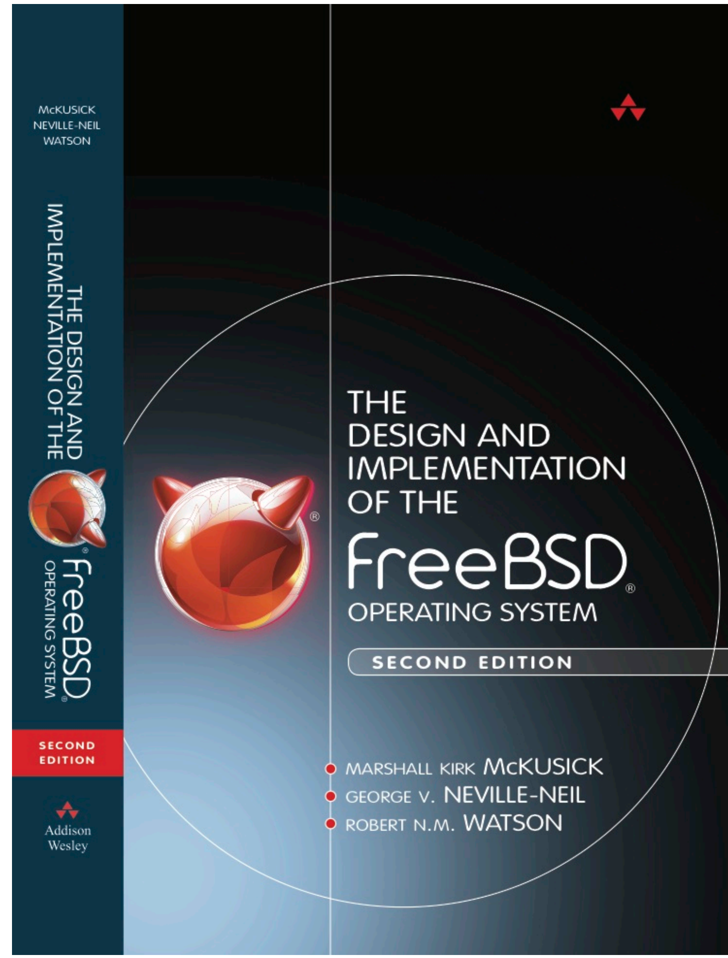
FreeBSD kernel

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



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

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 operating 'in kernel' (e.g., in system calls)
    - Kernel services (e.g., asynchronous work for VM, etc.)

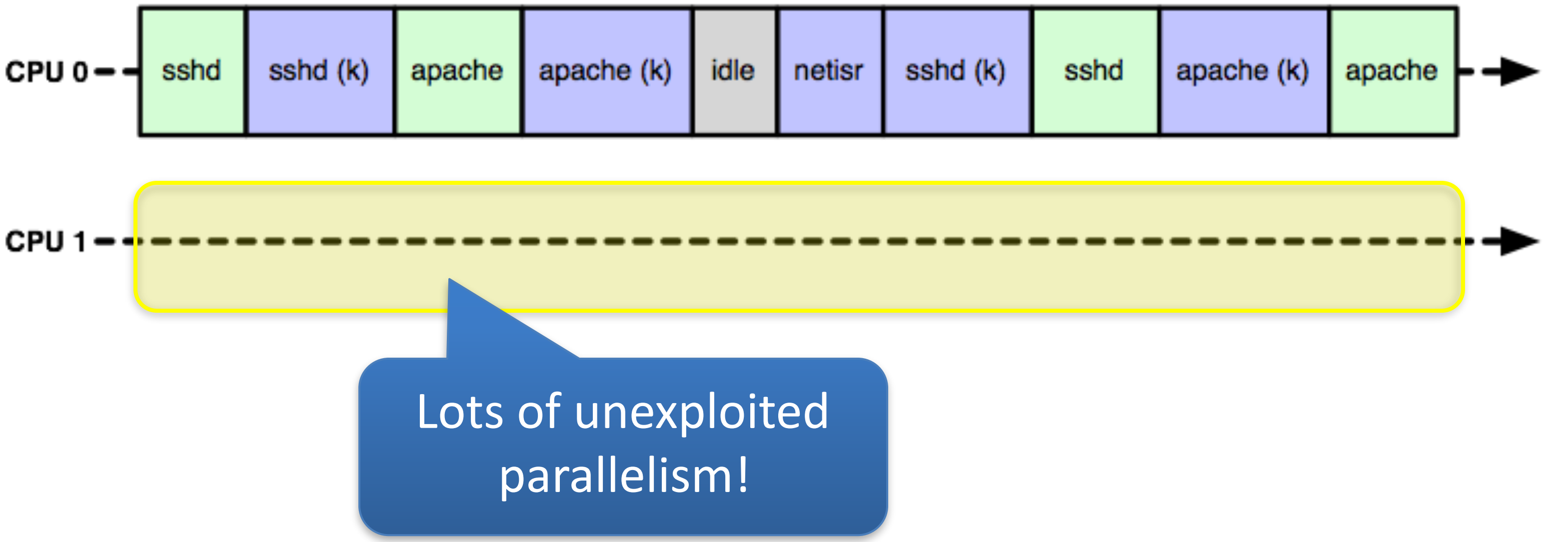
FreeBSD: before multiprocessing (2)

- 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 per 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), used in filesystems

Pre-multiprocessor scheduling



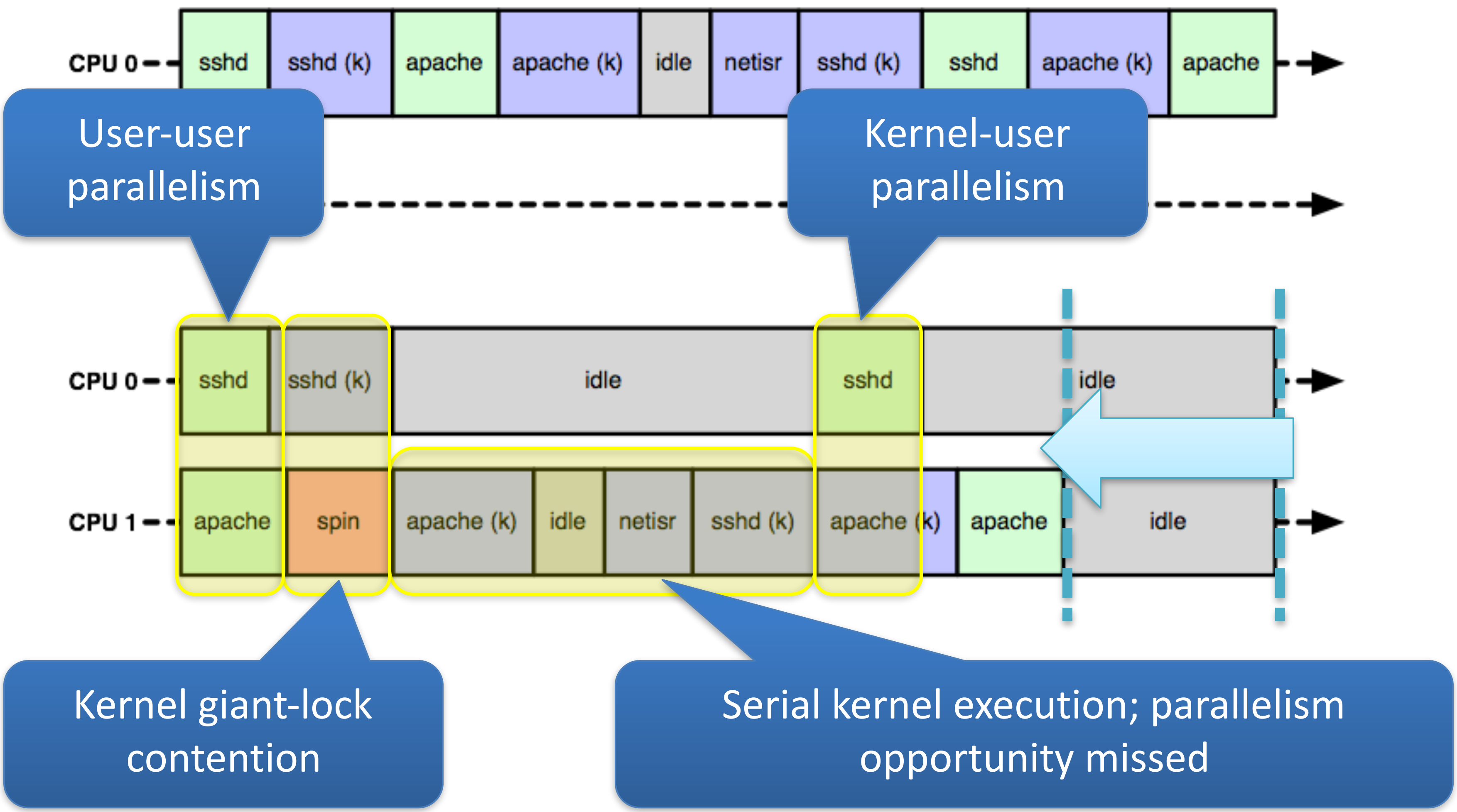
Hardware parallelism, synchronization

- 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!)

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

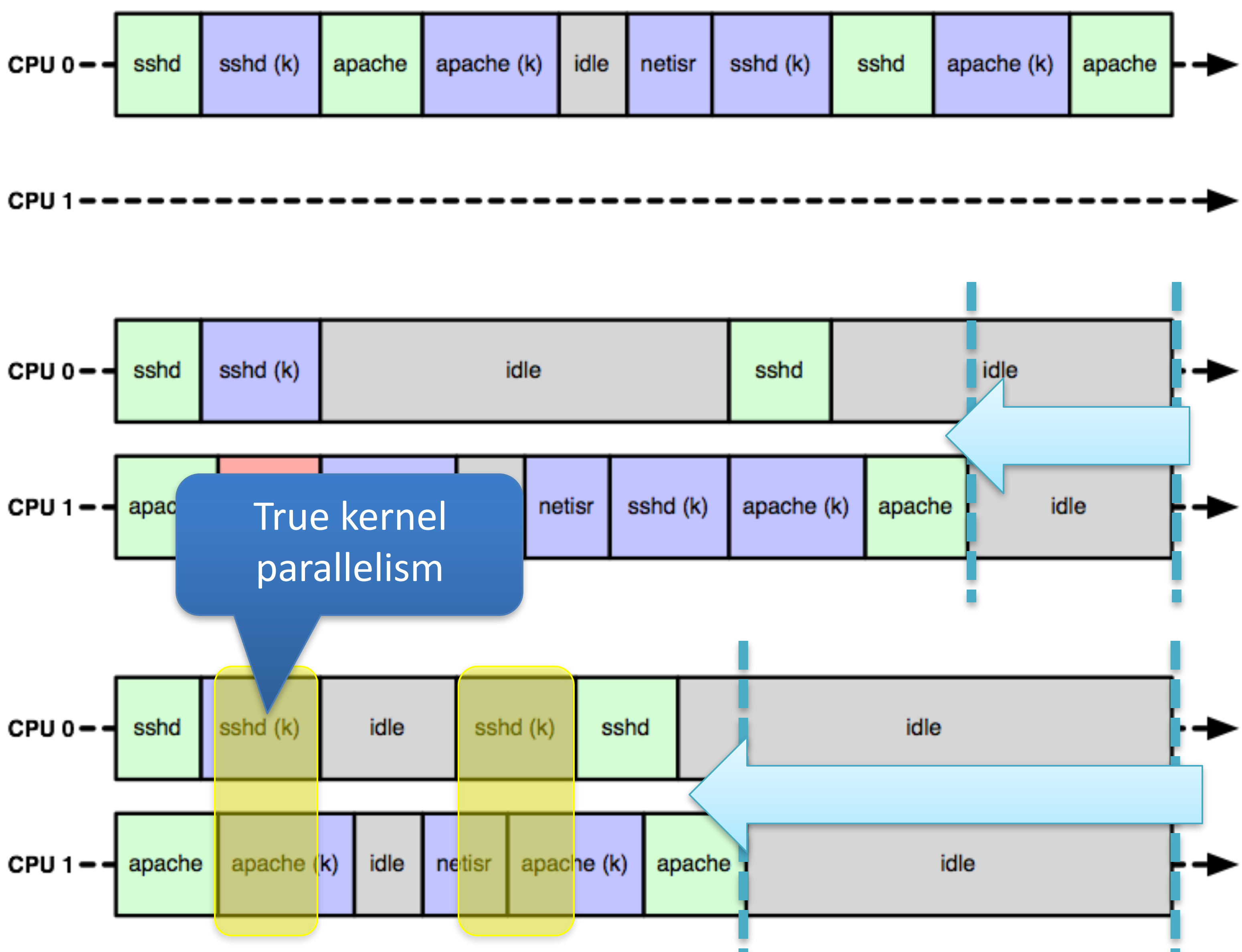
Giant-locked scheduling



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 has also now migrated away from semaphores

Fine-grained scheduling



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

- Avoiding deadlock is an essential aspect of the design

Kernel threads in action

```
robert@lemongrass-freebsd64:~> procstat -at
  PID    TID COMM             TDNAME           CPU  PRI STATE   WCHAN
    0 100000 kernel           swapper            1   84 sleep   sched
    0 100009 kernel           firmware taskq     0  108 sleep   -
```

Vast hoards of threads represent concurrent activities

Idle CPUs are occupied by an idle thread … why?

PID	TID	COMM	TDNAME	CPU	PRI	STATE	WCHAN
11	100003	idle	idle: cpu0	0	255	run	-
12	100024	intr	irq14: ata0	0	12	wait	-
12	100025	intr	irq15: ata1	1	12	wait	-
12	100008	intr	swi1: netisr 0	1	28	wait	-
3588	10017	sshd	-	0	122	sleep	select

```
   12 100005 intr             swi4: clock        1   40 wait    -
   12 100035 intr             irq1: atkbd0       1   16 wait    -
 3591 100069 tcsh             -                  0  152 sleep   pause
```

Device-driver interrupts execute in kernel ithreads

Asynchronous packet processing occurs in a **`netisr`** ‘soft’ ithread

Familiar userspace thread: `sshd`, blocked in network I/O (‘in kernel’)

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

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

WITNESS: global lock-order graph*

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

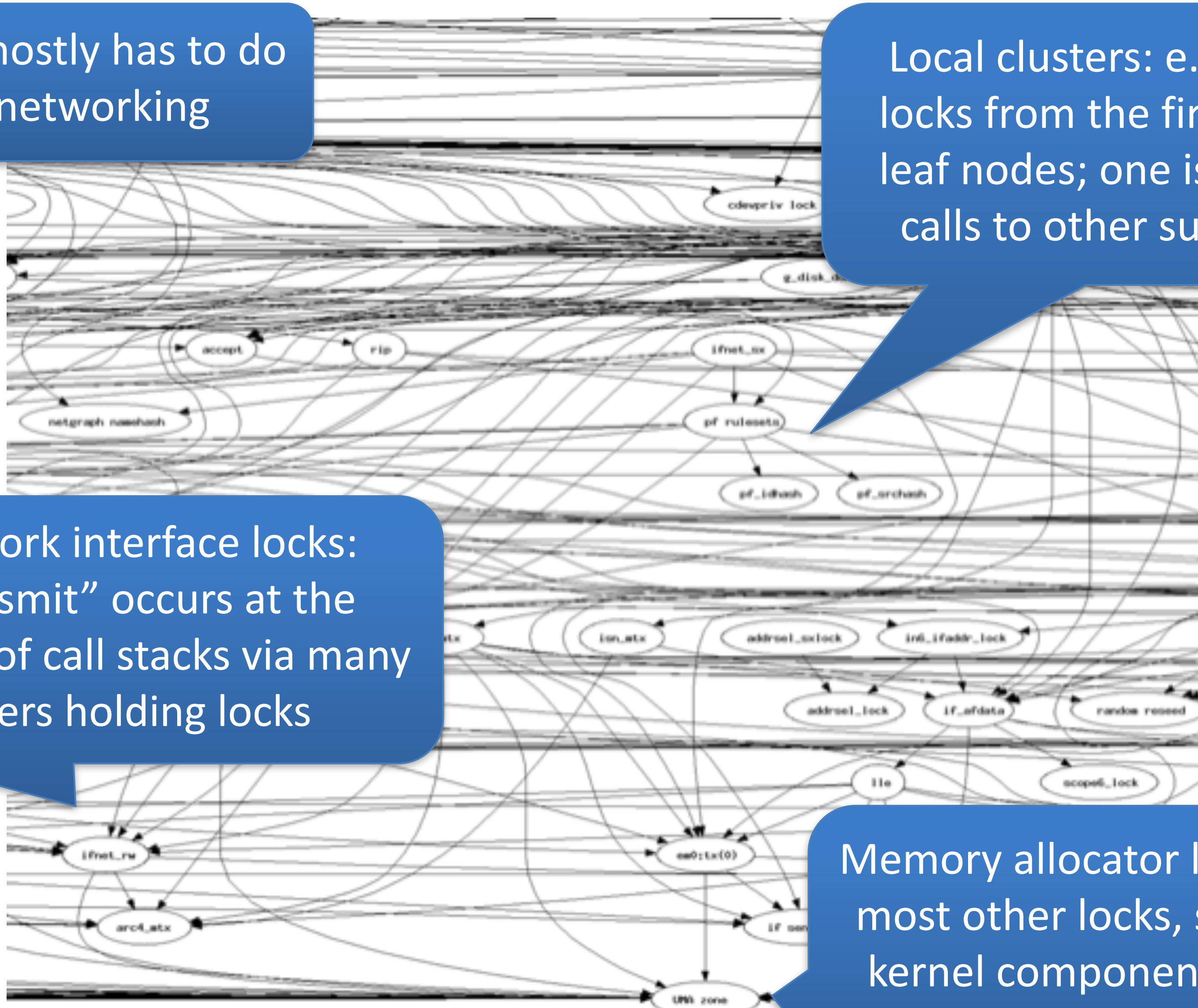
*

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

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 = 0x8
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?

Case study: the network stack (1)

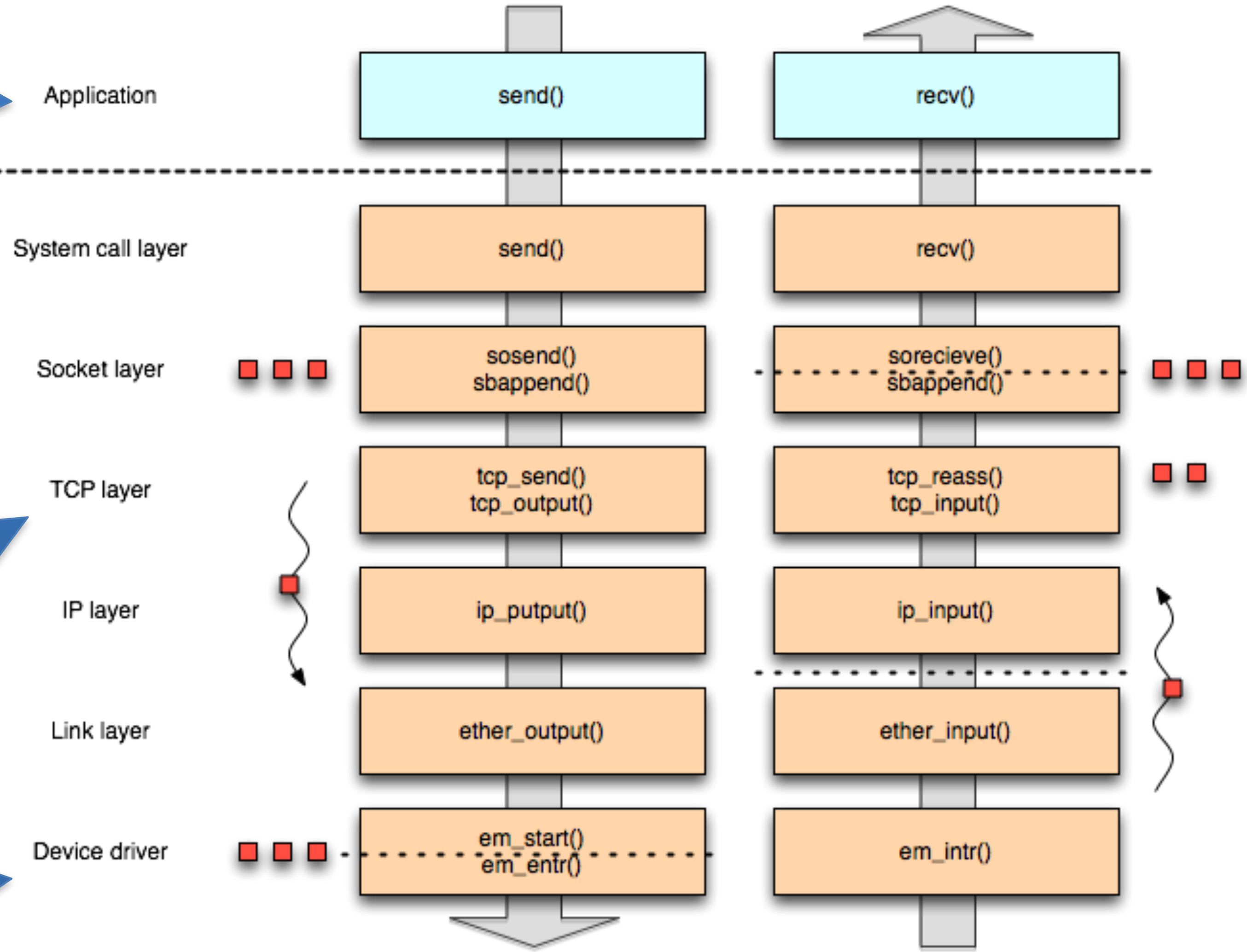
- What is a network stack?
  - Kernel-resident library of networking routines
  - Sockets, TCP/IP, UDP/IP, Ethernet, …
- Implements user abstractions, network-interface abstraction, protocol state machines, sockets, etc.
  - System calls: socket(), connect(), send(), recv(), listen(), …
- Highly complex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

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.

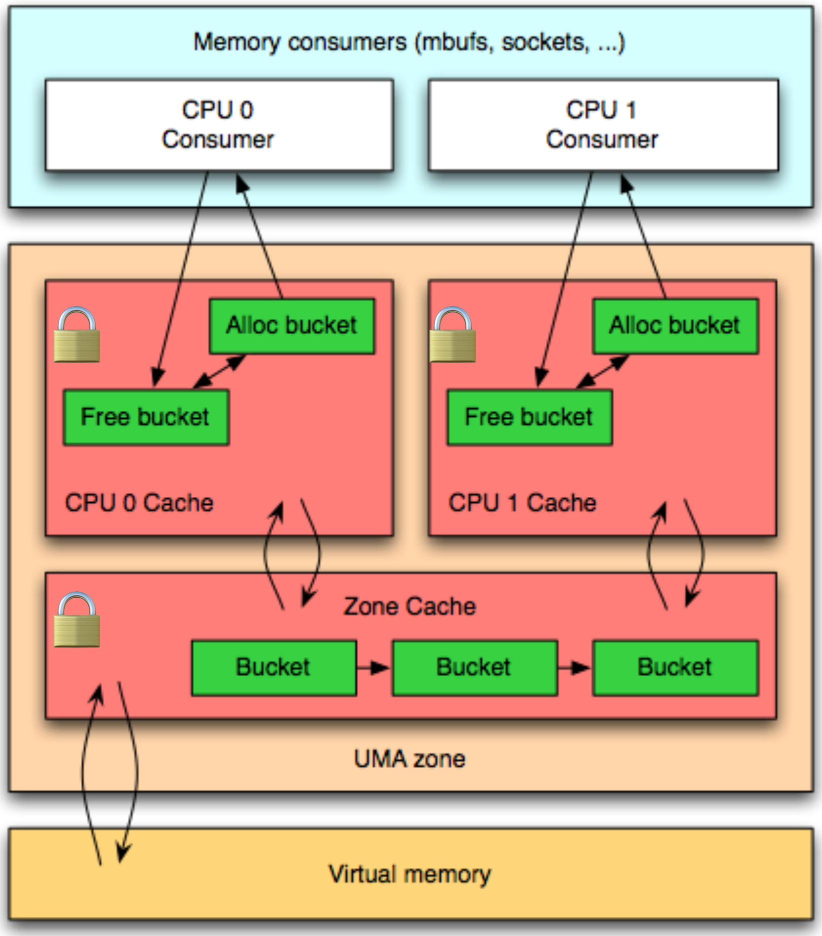
Case study: the network stack (2)

- 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

What to lock and how?

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

Example: Universal Memory Allocator (UMA)



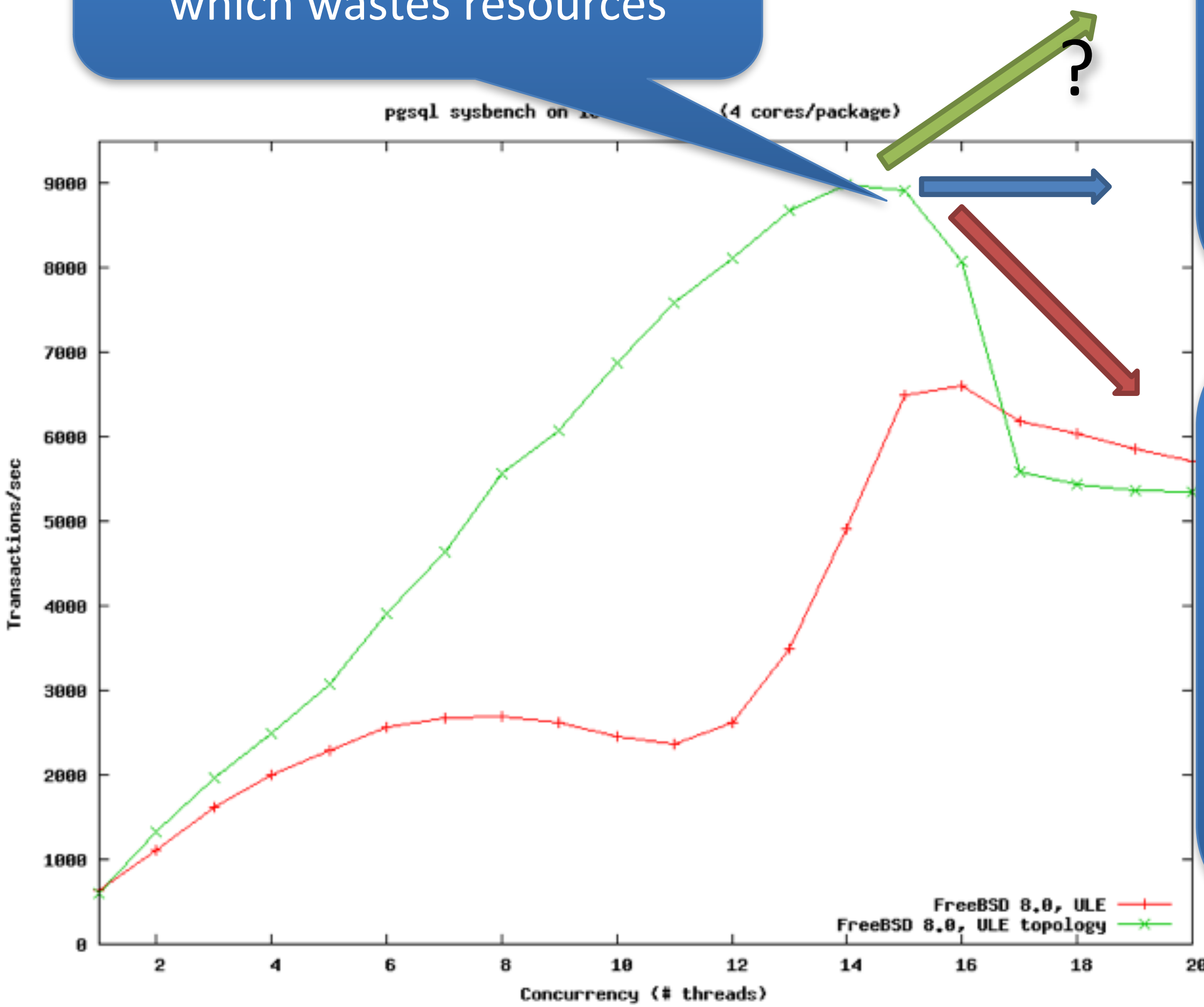
- Key kernel service
- Slab allocator
  - (Bonwick 1994)
- Per-CPU caches
  - Individually locked
  - Amortise (or avoid) global lock contention
- Some allocation patterns use only per-CPU caches
- Others require dipping into the global pool

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 OK between flows, just not within them
- Establish flow-CPU affinity can both order processing and utilize caches well

Scalability

Performance increase may reduce due to contention, which wastes resources



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
  - Read-mostly locks, read-copy-update (RCU)
  - Per-CPU data structures
  - Better distribute work to more threads to utilise growing core/hyperthread count
- Optimise for locality, not just contention: cache, NUMA, and I/O affinity
  - If communication is essential, contention is inevitable

Conclusions

- FreeBSD employs many of C&DS techniques
  - Multithreading within (and over) the kernel
  - Mutual exclusion, condition synchronization
  - Partial lock order with dynamic checking
  - Producer-consumer, lockless primitives
  - Also Write-Ahead Logging (WAL) in filesystems, …
- Real-world systems are really complicated
  - Composition is not straightforward
  - Parallelism performance wins are a lot of work
  - Hardware continues to evolve, placing pressure on software systems to utilise new parallelism
- Next: Distributed Systems!