Concurrent systems

Case study: FreeBSD kernel concurrency

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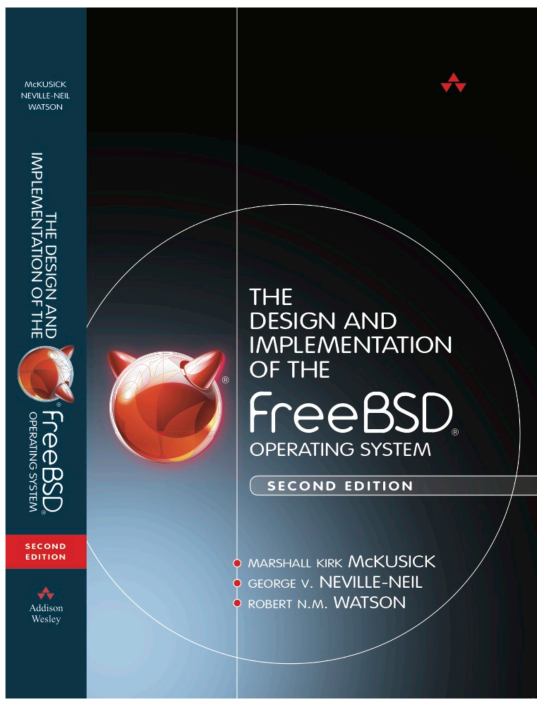
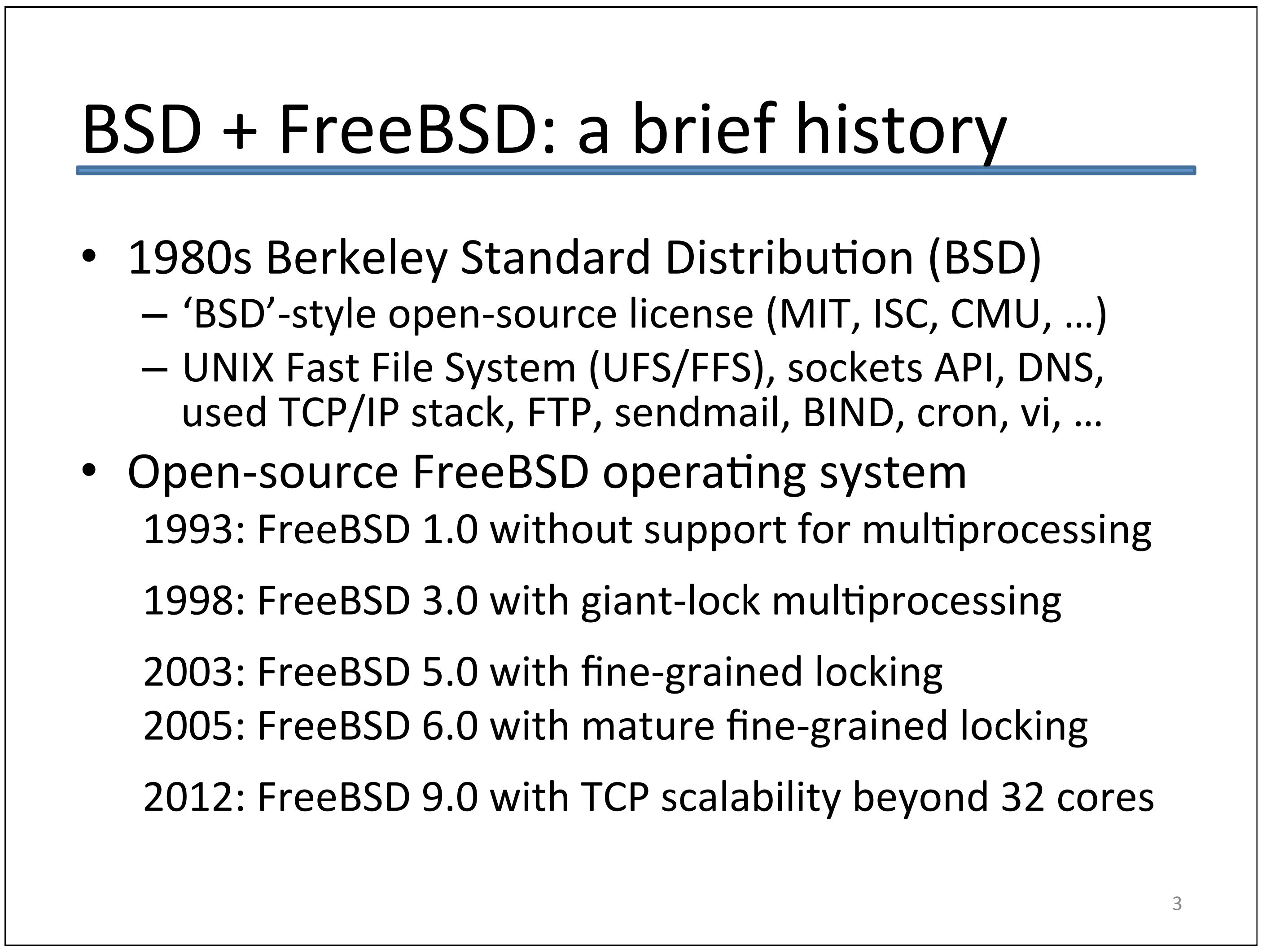
FreeBSD kernel

- Open-source OS kernel
  - **Large**: millions of LoC
  - **Complex**: thousands of subsystems, drivers, ...
  - **Very concurrent**: dozens or hundreds of CPU cores/ 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, Boston, MA, USA, September 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

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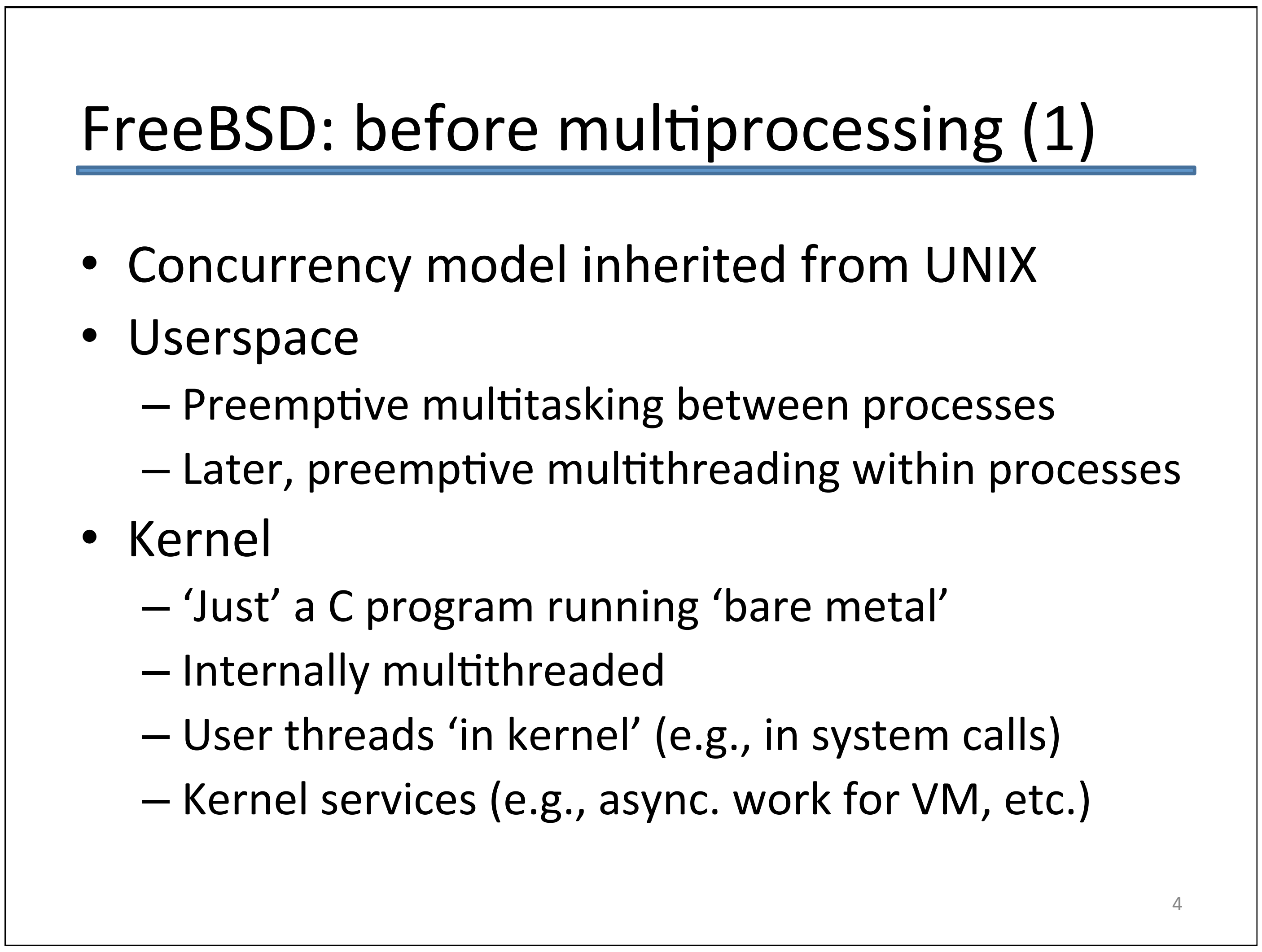

FreeBSD: before multiprocessing (1)

- 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.)

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FreeBSD: before multiprocessing (2)

- Cooperative multitasking within kernel
  - Except for interrupt handlers, non-preemptive kernel
  - Mutual exclusion as long as you don't `sleep()`
  - Implied global lock means local locks rarely required
- 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
- Primitive to build more complex synchronization tools
  - E.g., `lockmgr()` reader-writer lock can be held over I/O (sleep)
- *Critical sections* control interrupt-handler execution

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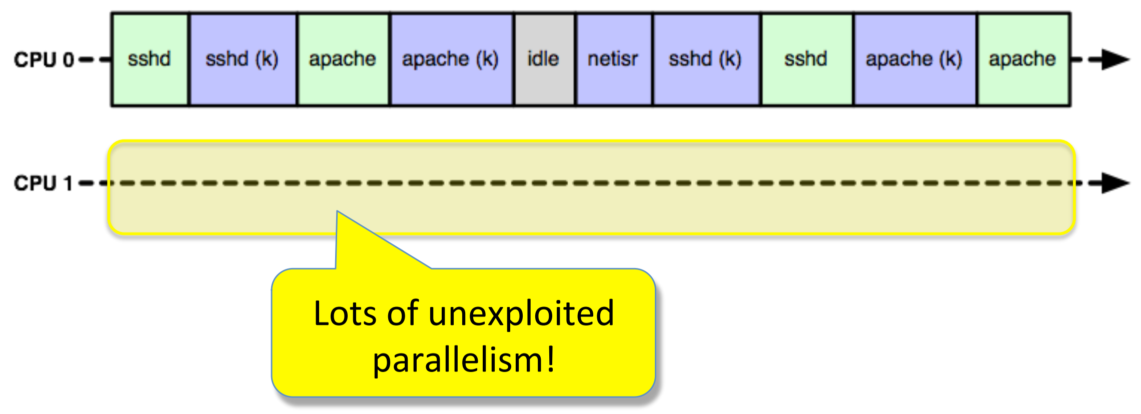
Pre-multiprocessor scheduling



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Hardware parallelism, synchronization

- Late 1990s: multi-CPU begins to move down market
  - In 2004: 2-processor a big deal
  - In 2014: 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!)

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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
  - No affinity model: schedule work on first available CPU
- ‘Giant’ spinlock around kernel
  - Acquire on syscall/trap to kernel; drop on return
  - In effect: kernel ‘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

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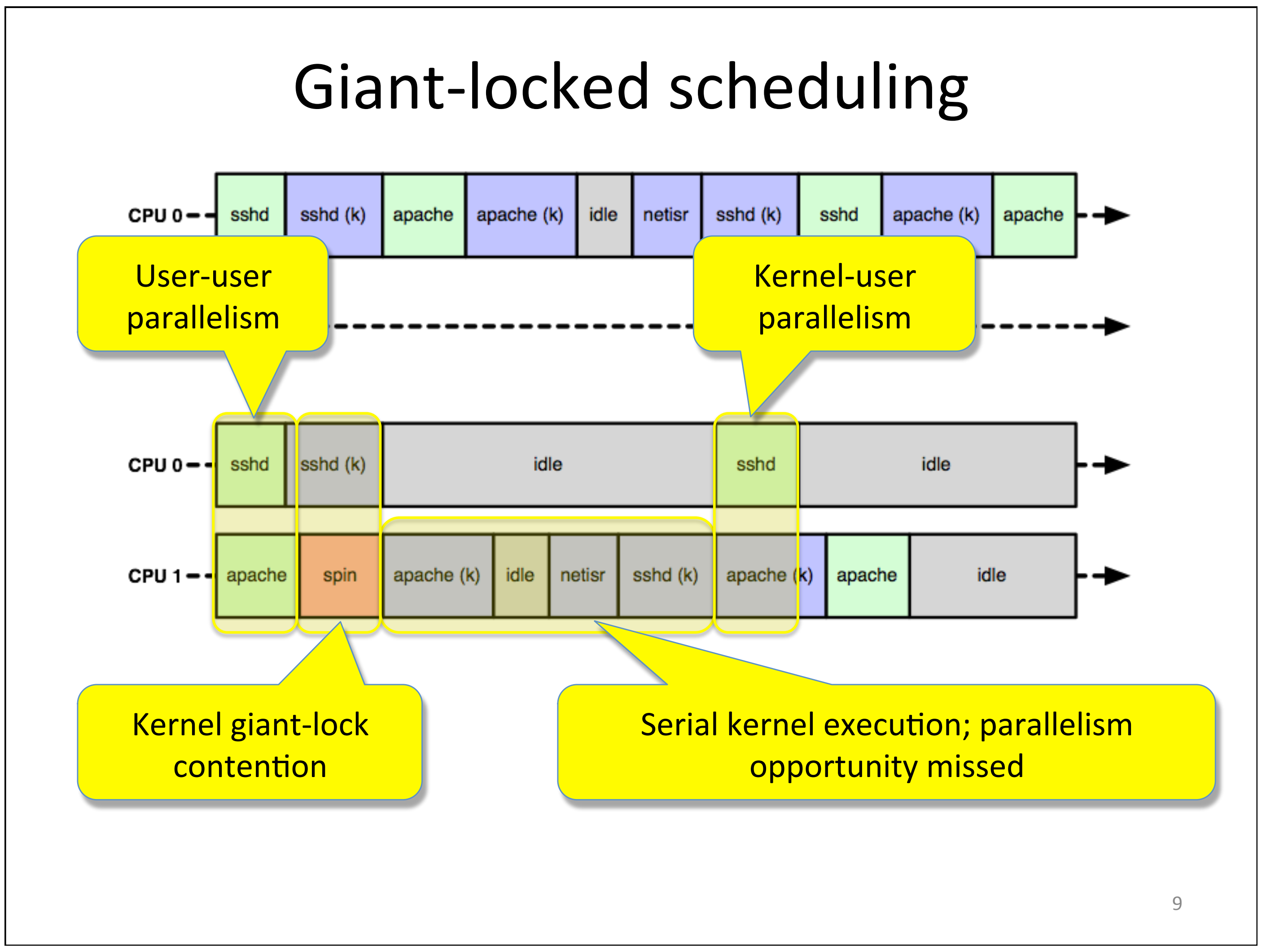
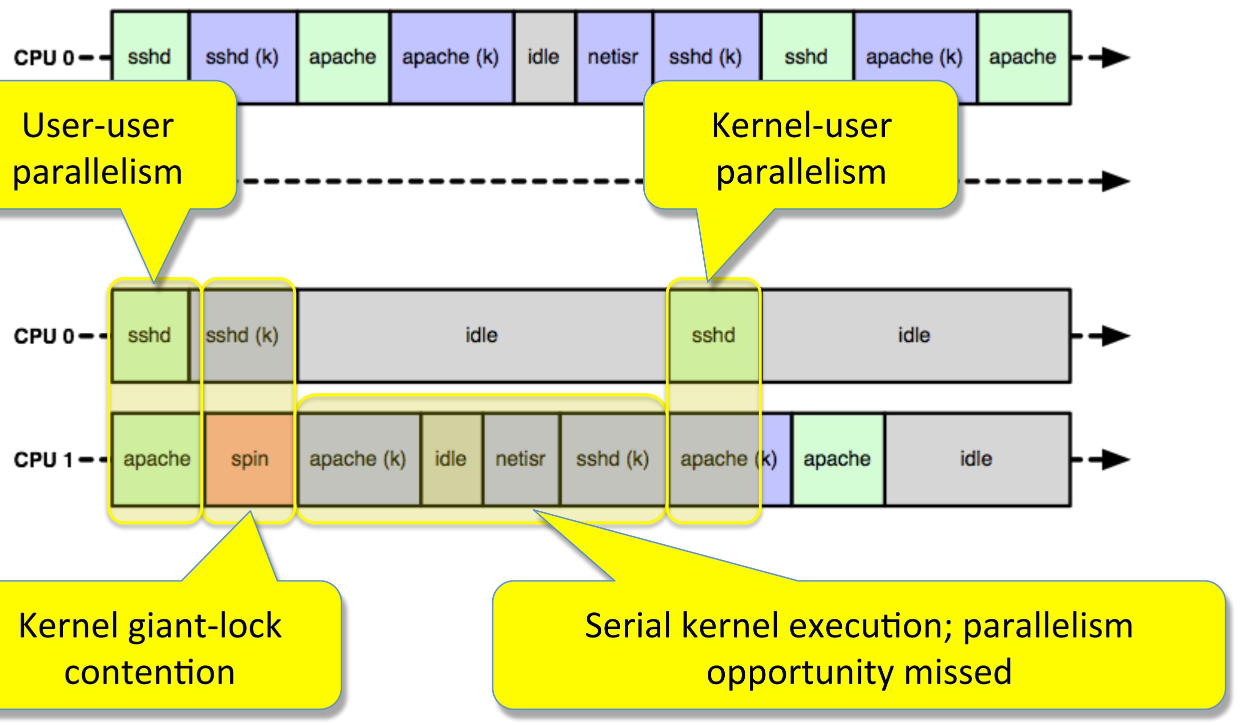


Giant-locked scheduling



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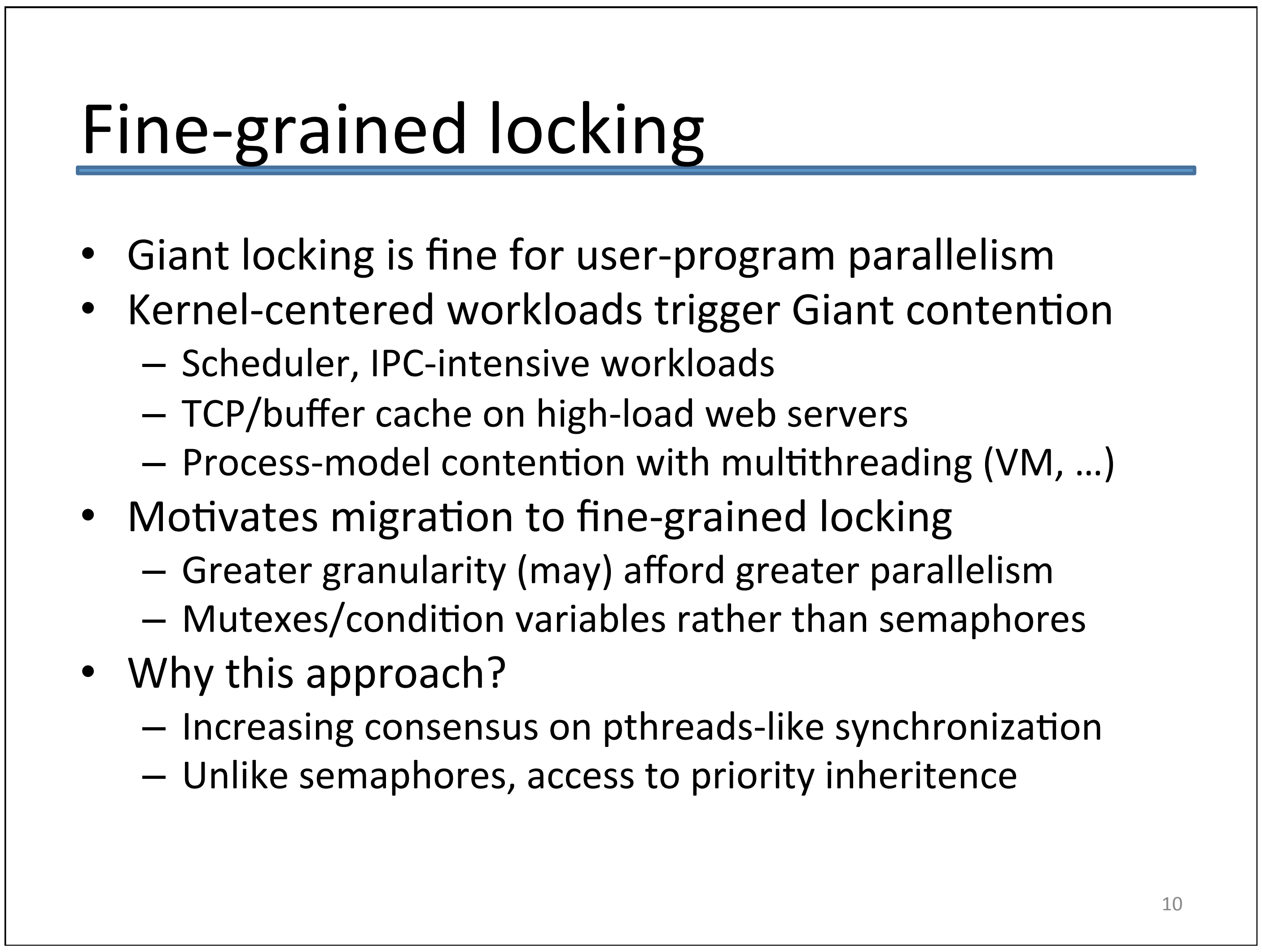

Fine-grained locking

- Giant locking is fine 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
- Why this approach?
  - Increasing consensus on pthreads-like synchronization
  - Unlike semaphores, access to priority inheritence

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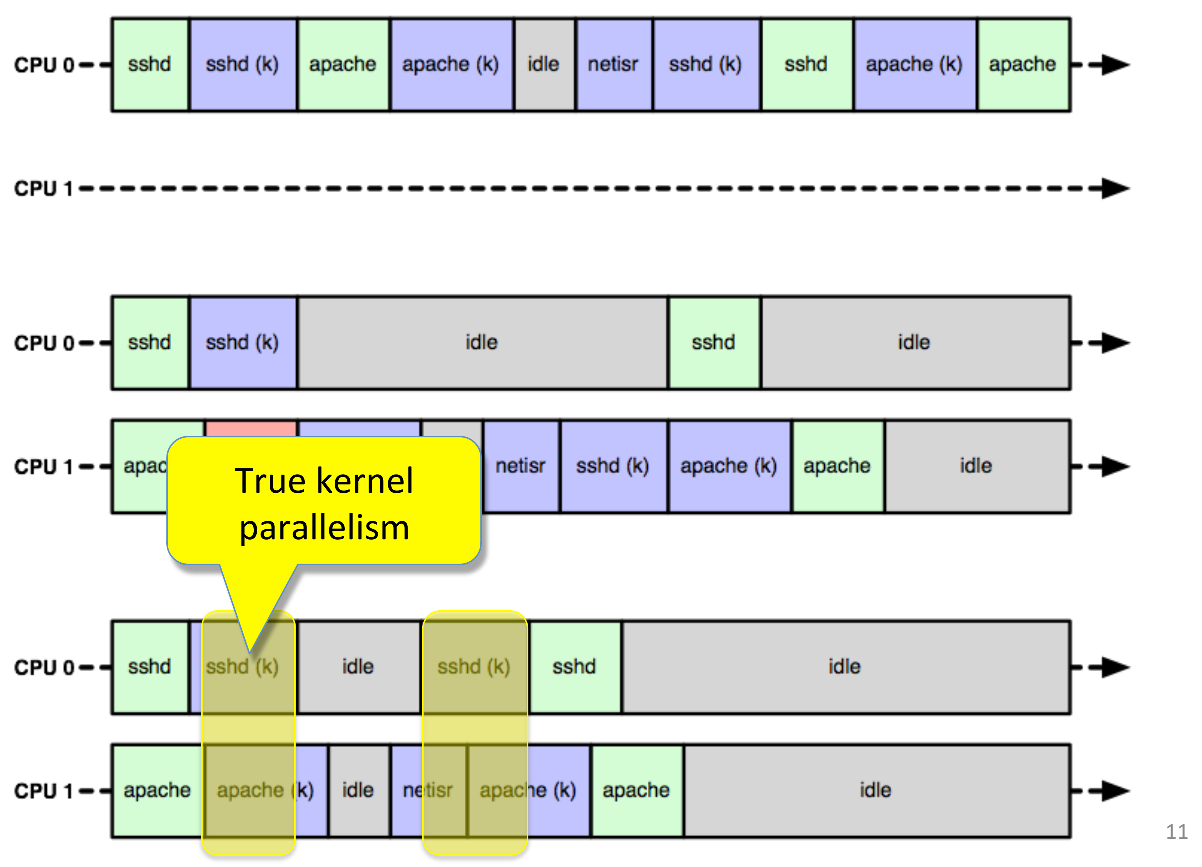
Fine-grained scheduling



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Kernel synchronization primitives

- Spin locks – scheduler, interrupt synchronization
- Mutexes, reader-writer, read-mostly locks
  - Most heavily used – different optimization tradeoffs
  - Sleep for only a 'bounded' period of time
- Shared-eXclusive (SX) locks, condition variables
  - May sleep for an unbounded period of time
  - Implied lock order: unbounded before bounded; why?
- Condition variables usable with any lock type
- Adaptive: sleeping is expensive, spin for a bit first
- Most primitives support priority propagation

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WITNESS lock-order checker

- Kernel relies on partial lock order to prevent deadlock (Recall dining philosophers)
- 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
- In-field lock-related deadlocks are (very) rare
- Unbounded sleep (e.g., I/O) deadlocks harder to debug
  - What thread should have woken up a CV being waited on?

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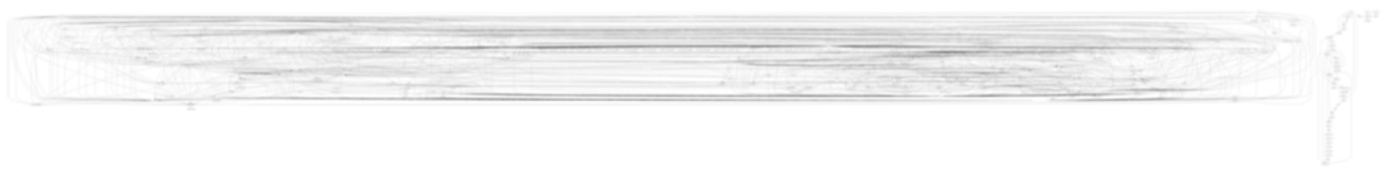
WITNESS: global lock-order graph*



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

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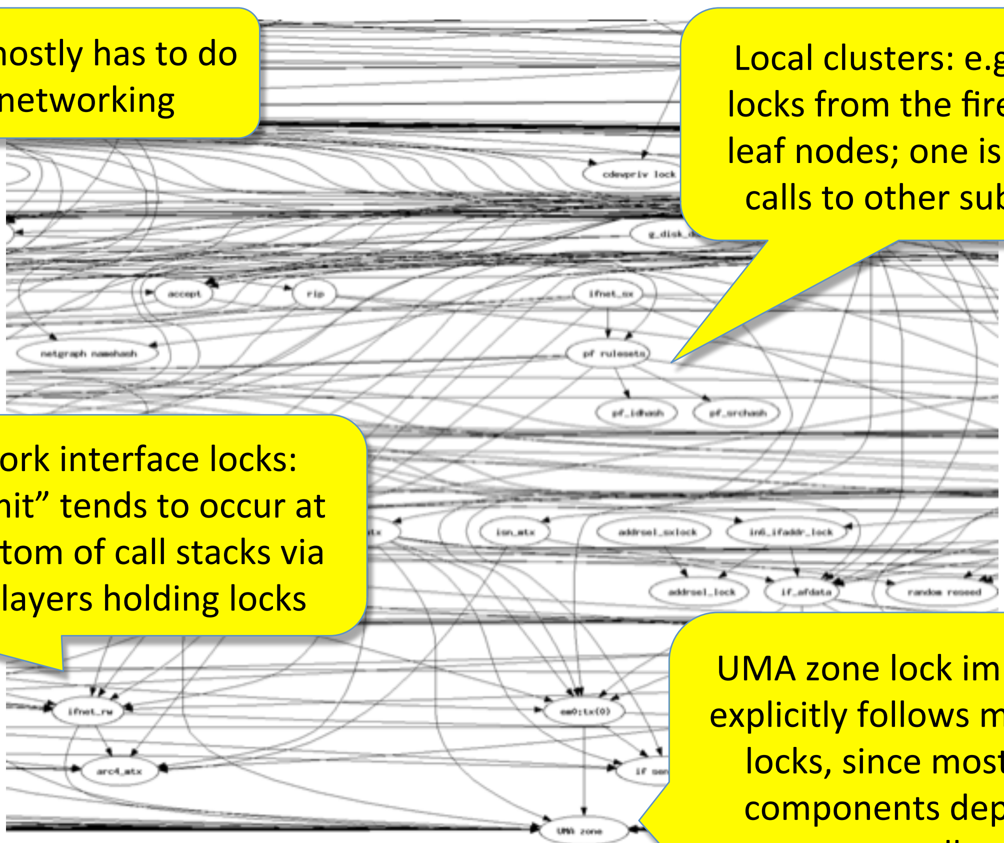
* Commentary on WITNESS full-system lock-order graph complexity; courtesy Scott Long, Netflix

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" tends to occur at the bottom of call stacks via many layers holding locks

UMA zone lock implicitly or explicitly follows most other locks, since most kernel components depend on memory allocation

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

WITNESS debug output

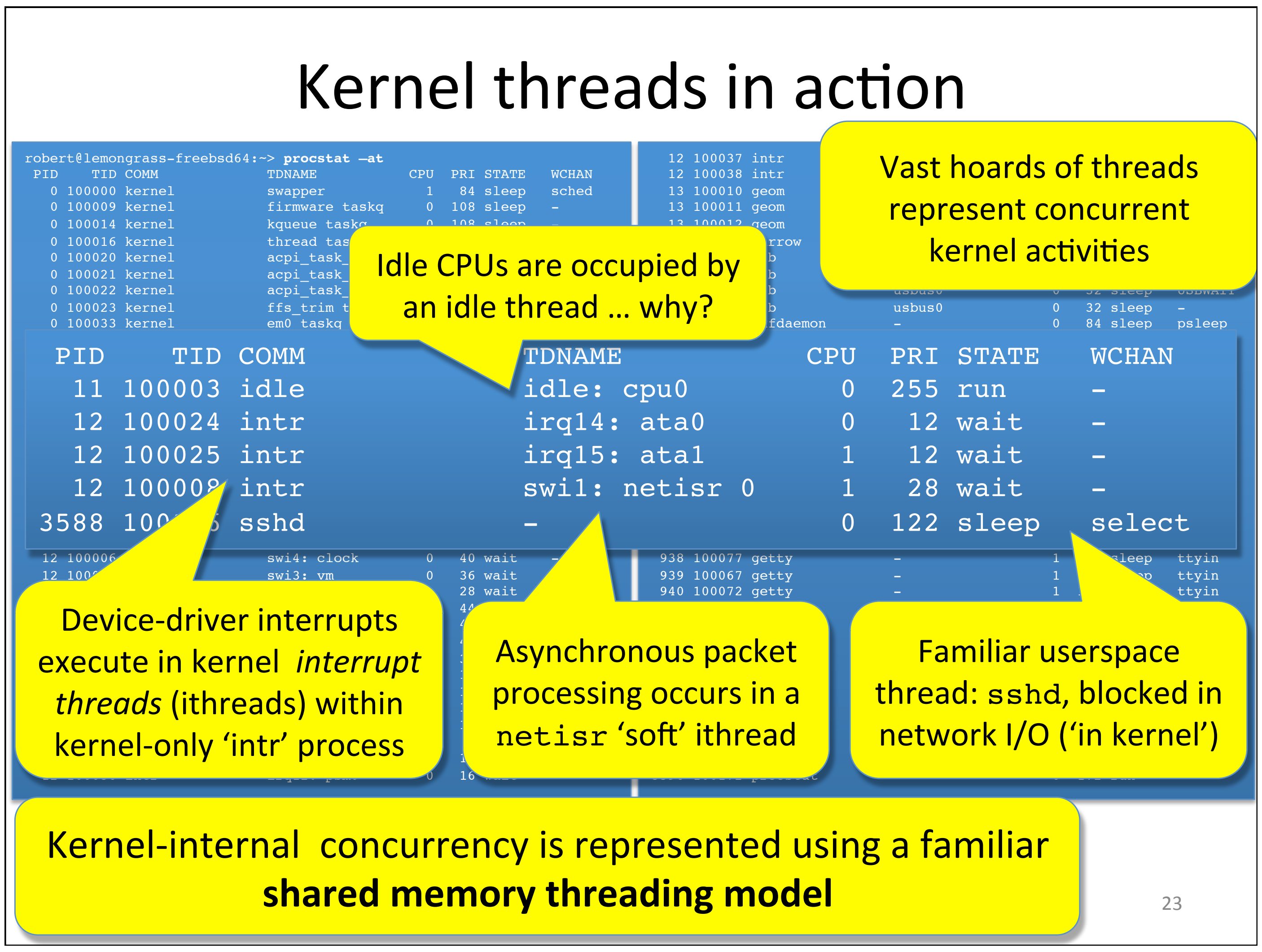
```
1st 0xffffff80025207f0 run0_node_lock (run0_node_lock) @ /usr/src/sys/
net80211/ieee80211_ioctl.c:1341
 2nd 0xffffff80025142a8 run0 (network driver) @ /usr/src/sys/modules/usb/
run/../../../dev/usb/wlan/if_run.c:3368

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 = 0x800de7aec, rsp =
0x7fffffffd848, rbp = 0x2a ---
```

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

Stack trace to acquisition that triggered cycle

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



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   -
    0 100014 kernel           kqueue taskq
    0 100016 kernel           thread tas
    0 100020 kernel           acpi_task_
    0 100021 kernel           acpi_task_
    0 100022 kernel           acpi_task_
    0 100023 kernel           ffs_trim t
    0 100033 kernel           em0 taskq
```

```
   12 100037 intr
   12 100038 intr
   13 100010 geom
   13 100011 geom
   13 100012 geom
             rrow
             b
             b
             b                usbus0
             b                usbus0             0   32 sleep   -
             fdaemon          -                  0   84 sleep   psleep
```

```
 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 100     sshd             -                 0  122 sleep   select
```

```
   12 100006                  swi4: clock        0   40 wait    -
   12 100                     swi3: vm           0   36 wait
                                                     28 wait
```

```
  938 100077 getty            -                  1          sleep   ttyin
  939 100067 getty            -                  1                  ttyin
  940 100072 getty            -                  1                  ttyin
```

Vast hoards of threads represent concurrent kernel activities
Idle CPUs are occupied by an idle thread … why?
Device-driver interrupts execute in kernel *interrupt threads* (ithreads) within kernel-only 'intr' process
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**

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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, sockets, protocol state machines, 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 'down' and 'up': packets come in, go out

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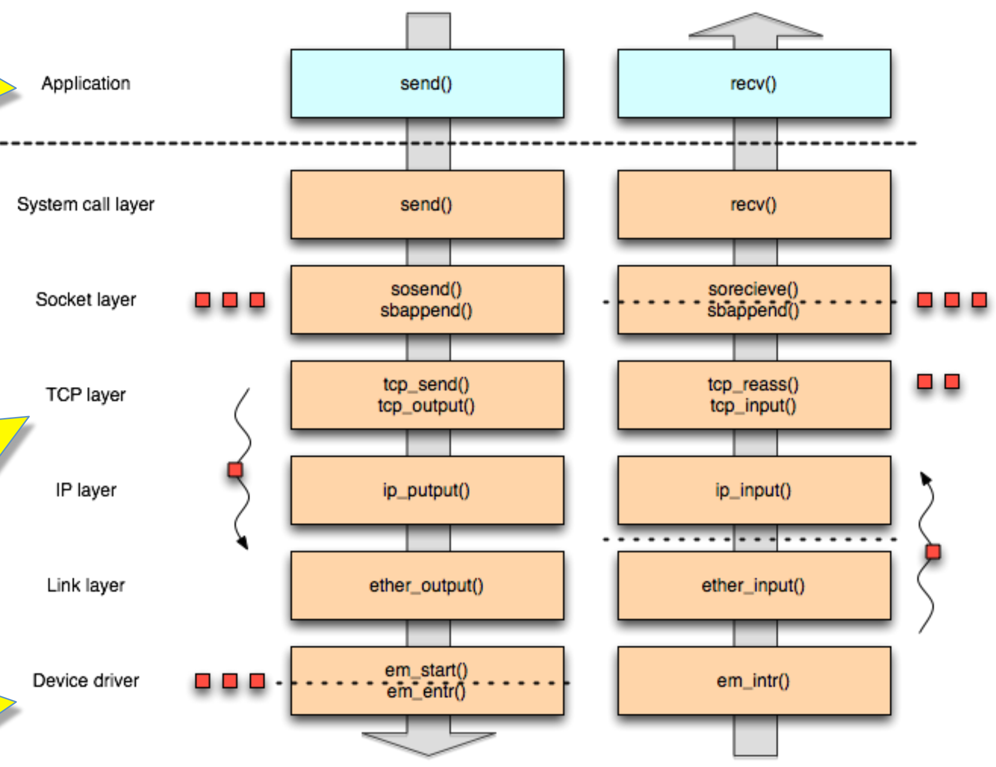
Network-stack work flows

Applications send, receive, await data on sockets

Data/packets processed; enqueued at various dispatch or buffering points

Packets go in and out of network interfaces



The work: adding/removing headers, calculating checksums, fragmentation/ defragmentation, segment reassembly, ensuring order, flow control, congestion, 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, optimize
  - Especially locking primitives themselves
- As hardware becomes more parallel, identify and exploit further concurrency opportunities
  - Add more threads, distribute more work

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What to lock and how?

- Fine-grained locking overhead vs. coarse-grained contention
  - Some contention is inevitable: reflects need for communication
  - Other contention is 'false sharing': side effect of data structure choices
- Principle: lock data, not code (i.e., not critical sections)
  - Key structures: network interfaces, sockets, work queues
  - Independent instances should be parallelizable
- 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 socket buffers)
  - V: Different locks at different layers (e.g., socket vs. TCP state)
- Things not to lock: packets in flight - mbufs ('work')

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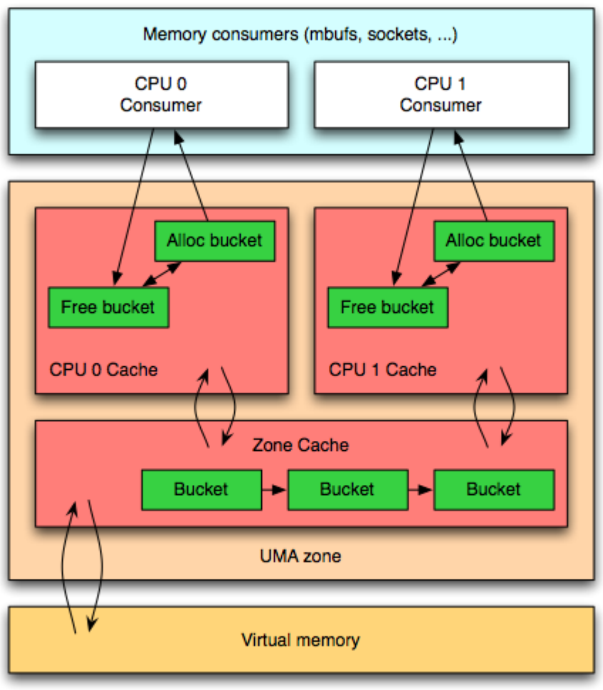
Example: universal memory allocator (UMA)



- Key kernel service
- Slab allocator
  - (Bonwick 1994)
- Object-oriented model
  - init/destroy, alloc/free
- Per-CPU caches
  - Protected by critical sections
  - Encourage cache locality by next allocating memory where last freed
  - Avoid zone-lock contention

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Work distribution

- Packets (mbufs) are units of work
- Parallel work requires distribution to multiple threads
  - Must keep packets ordered – or TCP gets cranky!
- Implication: strong per-flow serizliation
  - 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
- Establish flow-CPU affinity can both order processing and utilize caches well

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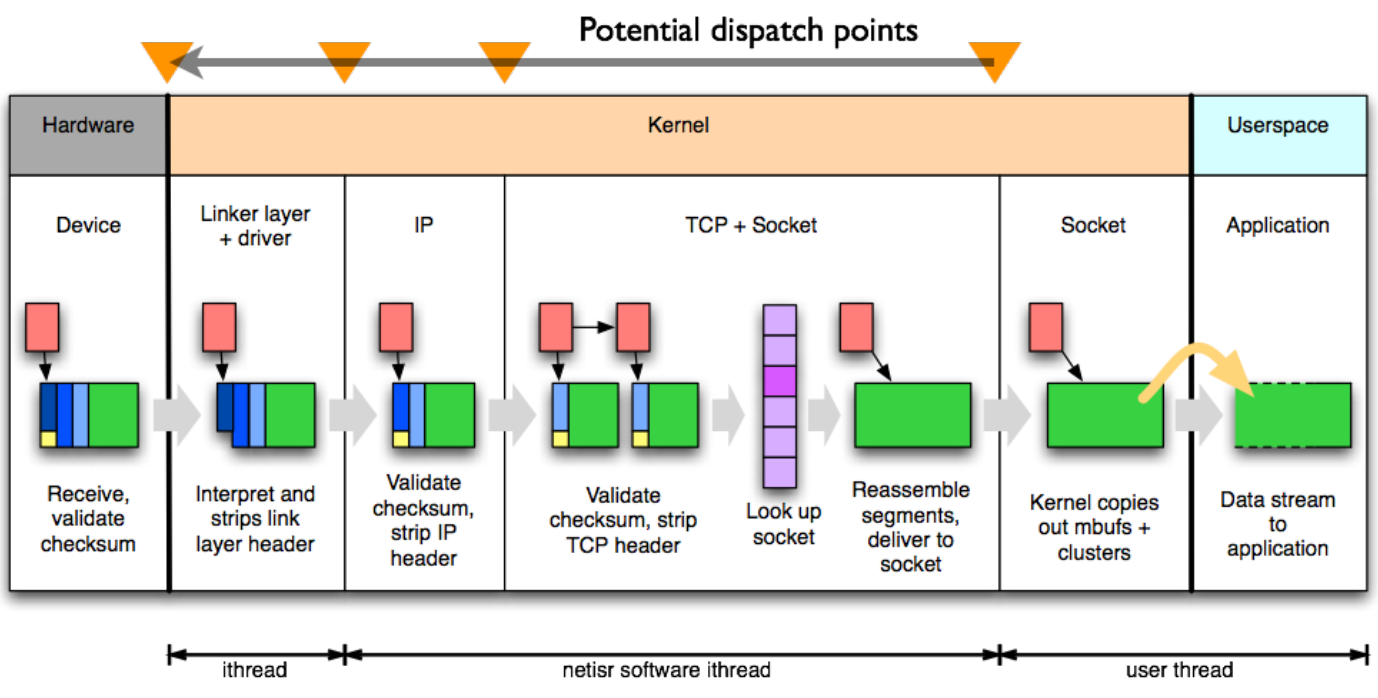
TCP input path


Potential dispatch points
Hardware
Kernel
Userspace
Device
Linker layer + driver
IP
TCP + Socket
Socket
Application
Receive, validate checksum
Interpret and strips link layer header
Validate checksum, strip IP header
Validate checksum, strip TCP header
Look up socket
Reassemble segments, deliver to socket
Kernel copies out mbufs + clusters
Data stream to application
ithread
netisr software ithread
user thread

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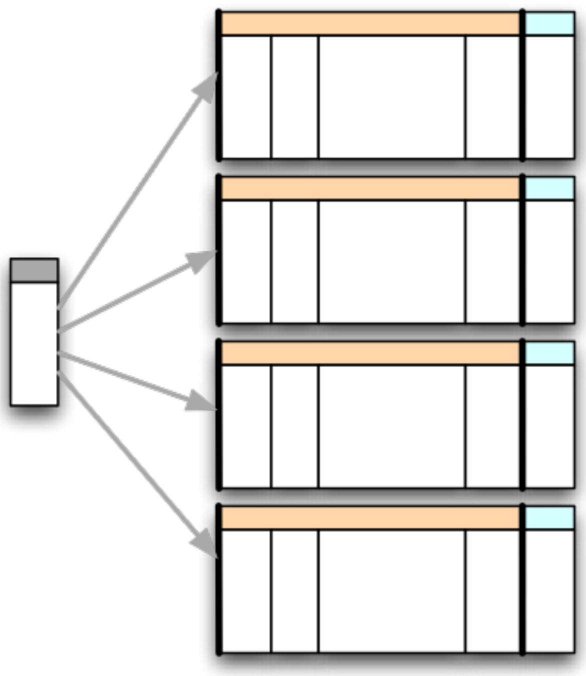
More recent trend: multiqueue NICs

- Key source of contention: locks around access to hardware devices
- Parallelism for hardware interface: give each NIC *n* input and output queues
- Flow order maintained by hashing IP/port-tuples in packet headers
- Each input/output queue pair assigned its own device-driver thread



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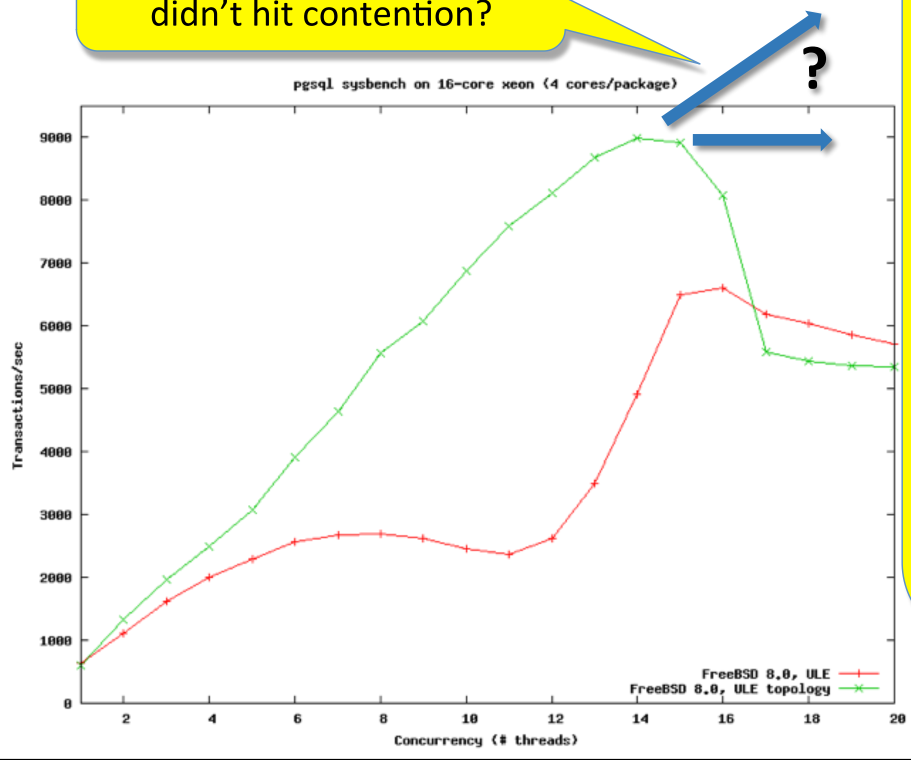
Scalability

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.

Another key idea:
performance collapse

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

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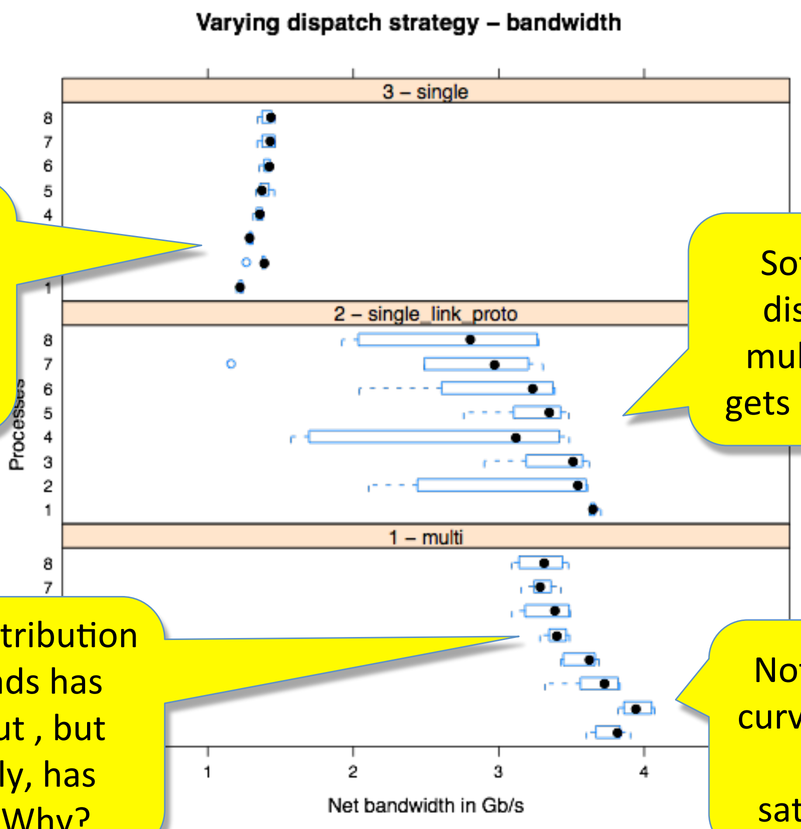
Complex interactions between scheduling and work



Single-threaded processing caps out a bit over 1Gb/s on this hardware

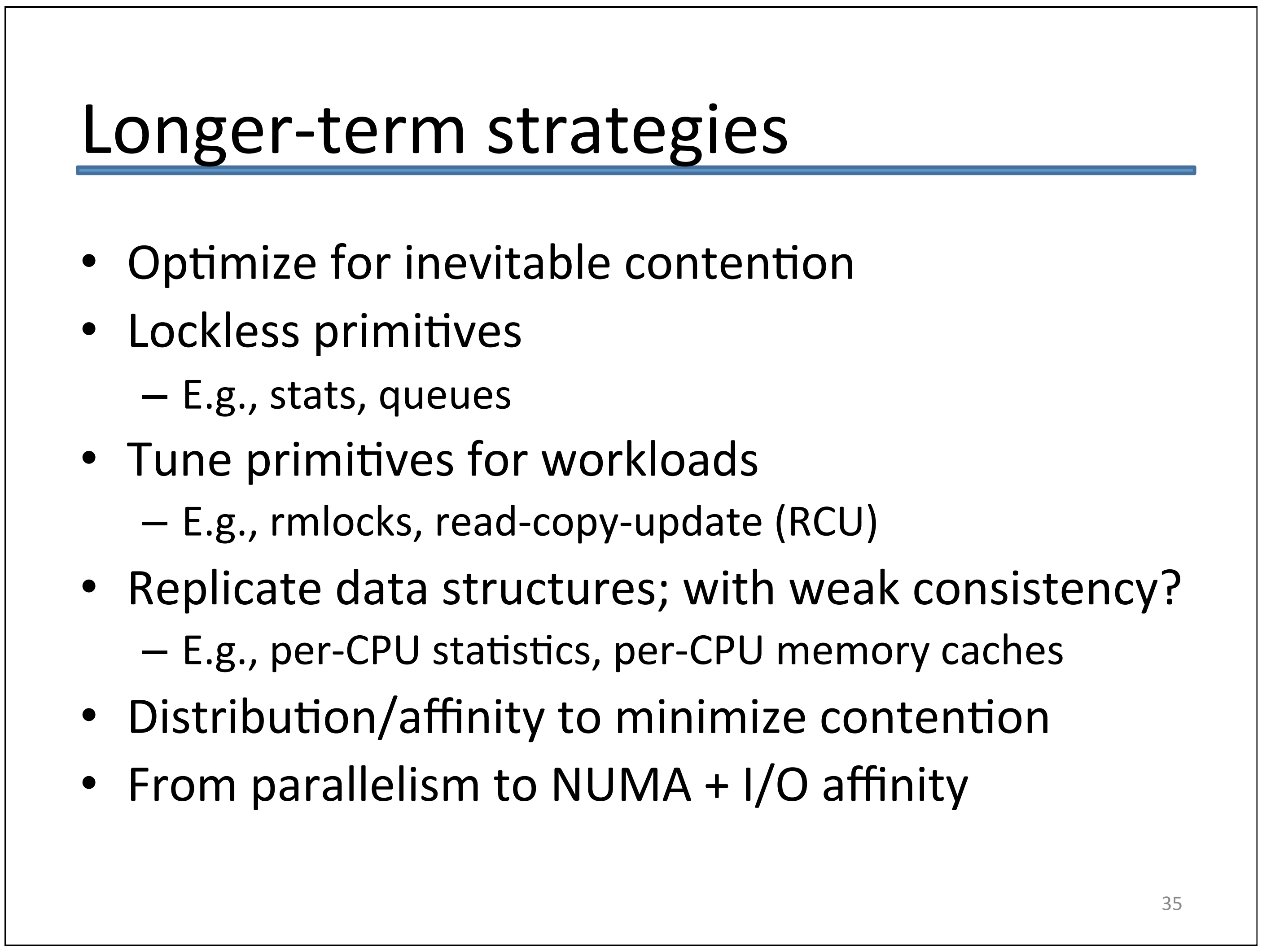
Software work distribution to multiple threads gets close to 4Gb/s

Hardware work distribution to multiple threads has higher throughput , but more importantly, has lower variance. Why?

Notice shapes of curves: parallelism helps, but saturation hurts

Changes in hardware impact software

- Hardware-design dynamics affect software:
  - Counting instructions ➞ cache misses
  - Lock contention ➞ cache-line contention
  - Locking ➞ find parallelism opportunities
  - Work ordering, classification, distribution
  - NIC offload of even more protocol layers
  - Vertically integrate distribution/affinity
  - DMA/cache interactions
- But: core principles for concurrency control (synchronization) remain the same



Longer-term strategies

- Optimize for inevitable contention
- Lockless primitives
  - E.g., stats, queues
- Tune primitives for workloads
  - E.g., rmlocks, read-copy-update (RCU)
- Replicate data structures; with weak consistency?
  - E.g., per-CPU statistics, per-CPU memory caches
- Distribution/affinity to minimize contention
- From parallelism to NUMA + I/O affinity

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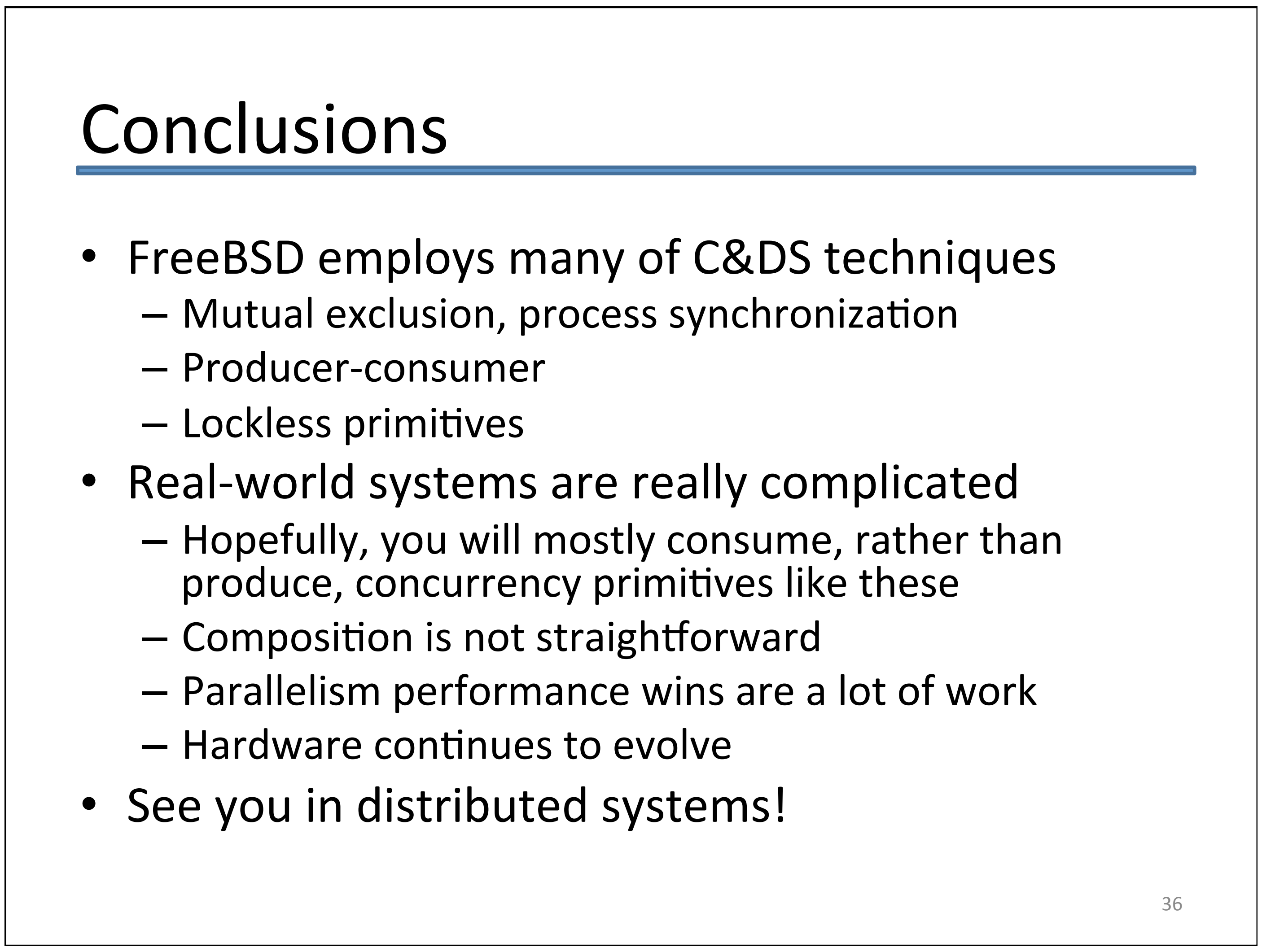

Conclusions

- FreeBSD employs many of C&DS techniques
  - Mutual exclusion, process synchronization
  - Producer-consumer
  - Lockless primitives
- 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!

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