Concurrent and distributed systems

Lecture 8: Concurrent systems case study

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Kernel concurrency

- Open-source FreeBSD operating-system kernel
  - Large: millions of lines of code
  - Complex: thousands of subsystems, drivers, ...
  - Extremely concurrent: supports 128+ HW threads
- Netapp, EMC, Panasas, Dell, Apple, Juniper, Cisco, McAfee, Netflix, Verio NY Internet, Yahoo!, Verisign, …
- Used at CL (Capsicum, CHERI, TESLA, SOAAP, ...)
- Employs many of the principles we have talked about

Brief history

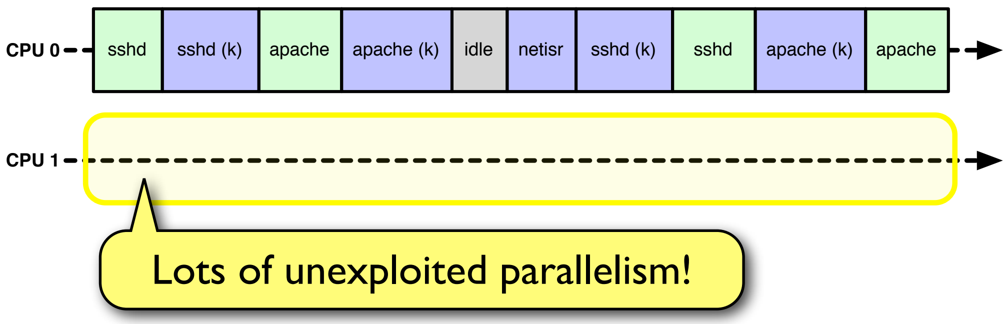
- 1980s DARPA-funded Berkeley Standard Distribution (BSD)
  - UNIX Fast File System (UFS/FFS), network sockets API, first widely used TCP/IP stack, FTP, sendmail, cron, vi, BIND, ...
- FreeBSD open-source operating system roughly 20 years old
  - 1993: FreeBSD 1.0 without support for multiprocessing
  - 1998: FreeBSD 3.0 with giant-lock kernel
  - 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
  - 2013*: FreeBSD 10.0 with non-uniform memory (NUMA)

* Or perhaps early 2014?

Before multiprocessing

- Preemptive multitasking and multithreading for user processes
- Kernel internally multithreaded
  - Represent user threads "in kernel" during system calls/page faults
  - Kernel services utilise threads (e.g., VM, file system, …)
- Most kernel code runs under mutual exclusion
  - Implied condition variables associated with every kernel address
    - `struct foo x;`
    - `sleep(&x, secs)`, `wakeup(&x)`
  - `lockmgr` reader-writer lock can be held over blocking I/O
  - Sleeping with `lockmgr` or `sleep` triggers context switching
- Critical sections prevent untimely preemption by interrupts

Pre-multiprocessor scheduling



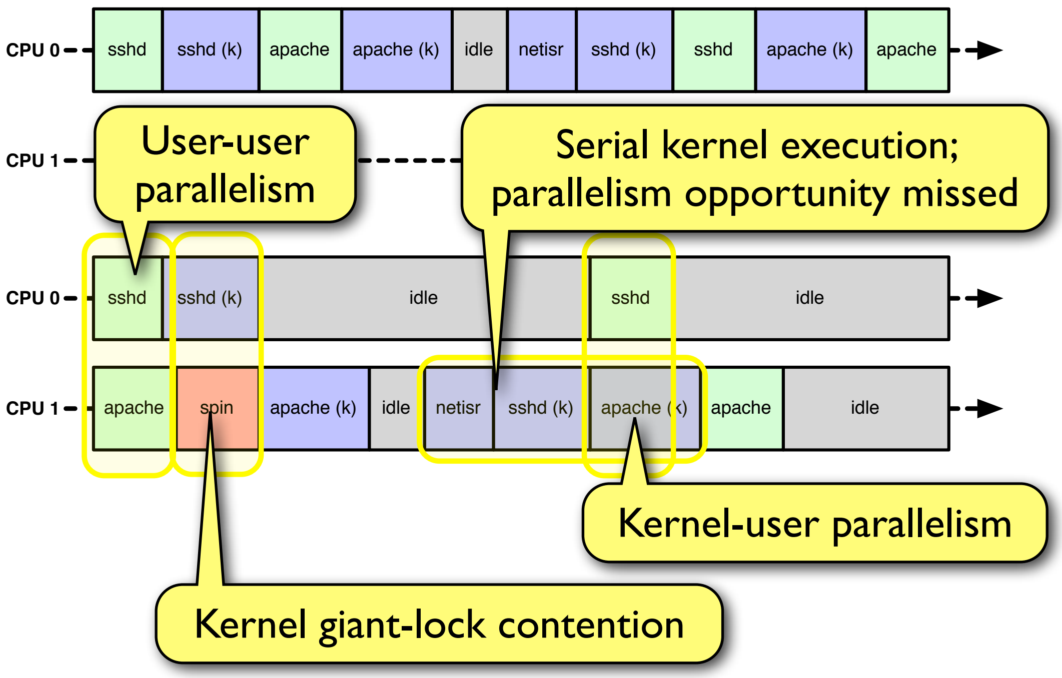
CPU-level synchronisation

- Late1990s: commodity multi-CPU hardware available from Intel, others
- Architecture-specific atomic operations
  - Compare-and-swap
  - Test-and-set
  - Load linked/store conditional
- Inter-processor interrupts (IPIs)
  - One CPU can trigger an interrupt on another, running handler
- Vendor-specific extensions
  - MIPS inter-thread message passing
  - Intel TM support

Giant locking the kernel

- FreeBSD follows in the footsteps of Cray, Sun, etc.
- Parallel user programs with non-parallel kernel
  - "Giant" spinlock around kernel
  - Acquire on syscall/trap to kernel
  - Drop on return
  - Kernel "migrates" between CPUs on demand
- Interrupts
  - If interrupt delivered on CPU *X* while kernel is running on CPU *Y*, forward interrupt to *Y*

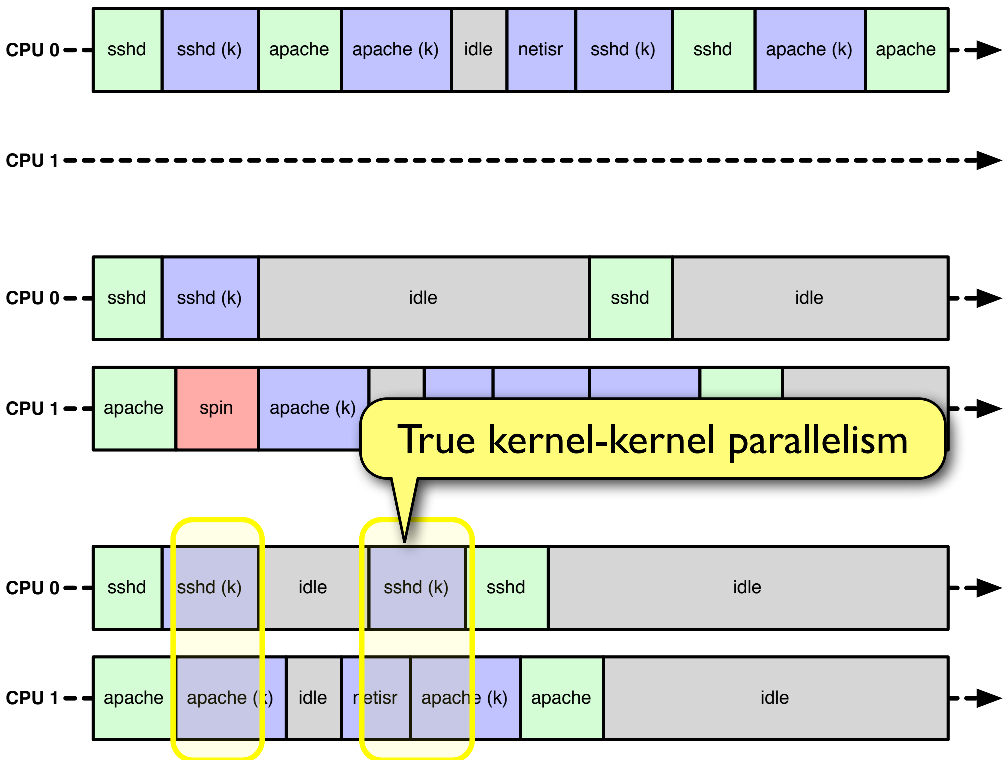
Giant-locked scheduling



Fine-grained locking

- Giant-locked kernels good for parallel user programs
- But kernel-centred workloads trigger Giant contention
  - E.g., heavy TCP use in web-server workloads
- Motivates move to fine-grained locking
  - FreeBSD adopts *pthreads*-like model for the kernel
  - Familiar multi-threading environment
  - Mutexes/condition variables rather than semaphores
  - Why? Among other things: priority inheritance

Fine-grained scheduling



Software synchronisation

- Spin locks
- Sleepable locks with different use cases/optimisations
- Mutexes, reader-writer (RW), read-mostly (RM) locks
  - Will sleep for only a **bounded period** of time
- Shared-exclusive (SX) locks
  - May sleep for an **unbounded period** of time
- Implied lock order: unbounded- before bounded-period locks
- Most lock types support priority propagation
- Condition variables, usable with all lock types

Why? Mutexes are used only for "short" waits, so safe to use them (and wait on them) implementing "long" waits -- e.g., disk I/O

Spinlocks

- Synchronisation internal to the scheduler, interrupts
- E.g., protect sleep queues for mutexes and condition variables
- Spinlock acquire:
  - Disable interrupts
  - Spin on test-and-set to replace `MTX_UNOWNED` with *thread ID*
- Spinlock release:
  - Set lock to `MTX_UNOWNED`
  - Enable interrupts
- More complicated cases involve **lock recursion**

Interrupt handlers borrow (preempt) contexts synchronously. If a handler tries to acquire a spinlock held by the context it has preempted, deadlock!

Mutexes, RW locks

- Like semaphores, sleep rather than [always] spinning
  - Unlike spinlocks, mutexes allow interrupts + preemption
  - Implement priority inheritance
- Sleeping is really expensive (scheduler-internal spinlocks)
  - *Adaptive mutexes* address common-case contention
  - Spin if the holder of the lock executing on another CPU
- `rwlocks` are a variation supporting read locking
- Mutexes, rwlocks for most in-kernel synchronisation

Mutex KPIs

- Very similar to *pthread* mutexes in every way
- `struct mtx m;`
- `void` **`mtx_init`**`(m, name, type, opts)`
- `void` **`mtx_destroy`**`(m)`
- `void` **`mtx_lock`**`(m)`
- `void` **`mtx_unlock`**`(m)`
- `int` **`mtx_trylock`**`(m)`
- `void` **`mtx_assert`**`(m)`

Name and type used by WITNESS lock order verifier - more on that later

Notice: no confusing error values from lock and unlock!

Condition variables

- Pretty much as we talked about for POSIX - condition variables are used with locks, but not bound to specific monitors
- `void cv_init(cv, desc)`
- `void cv_destroy(cv)`
- `void cv_wait(cv, lo)`
- `void cv_wait_sig(cv, lo)`
- `int  cv_timedwait(cv, lo)`
- `int  cv_timedwait_sig(cv, lo)`
- `void cv_signal(cv)`
- `void cv_broadcast(cv)`

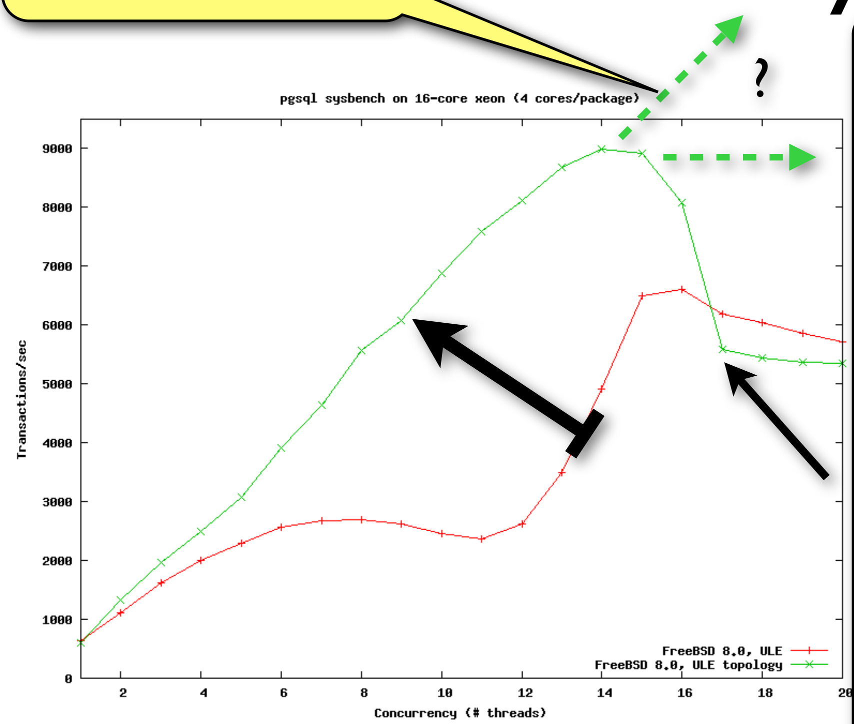
String description allows `ps` to show what CV thread is waiting on - useful for debugging!

Timed waits for I/O timeouts; `_sig` variants interruptible by UNIX signals

lo can be any type of lock object, including mutexes, rwlocks, etc.

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

Scalability



Key idea:
speedup

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

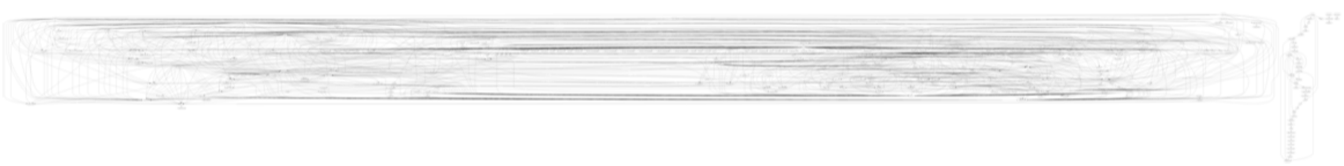
Another key idea:
performance collapse

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

WITNESS

- FreeBSD kernel relies (almost) entirely on lock order to prevent deadlock
- WITNESS is a lock order debugging tool
  - Warns when a deadlock **might** have occurred due to cycles
  - Enabled only in debugging kernels due to expense (~15%+)
- Tracks both statically declared and dynamic lock orders
  - Static orders most commonly *intra-module*
  - Dynamic orders most commonly *inter-module*
- FreeBSD rarely experiences lock-related deadlocks due to partial order
- However, I/O and sleep deadlocks are harder to detect/debug
  - Condition variables make it hard to know what thread is waited on

WITNESS
global lock order graph*



* Turns out that the global lock order is pretty complicated

*

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

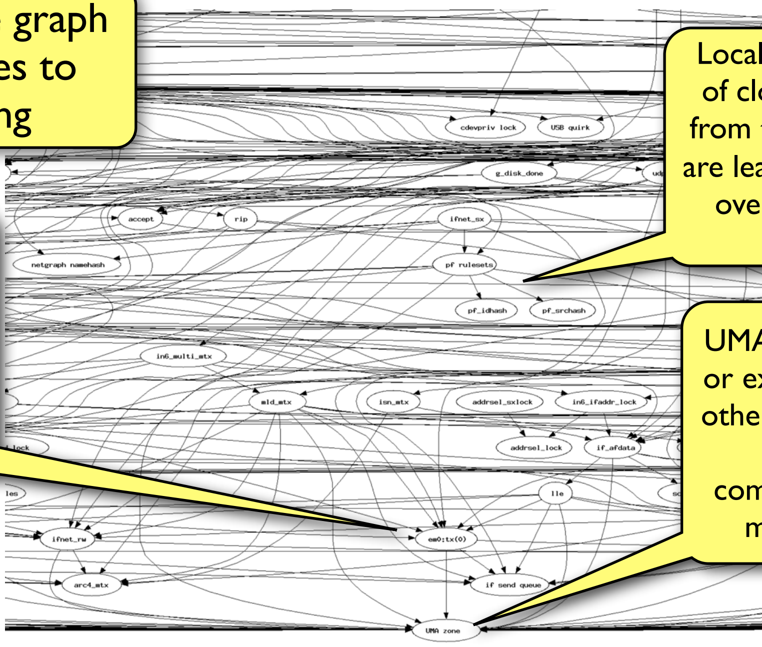
Excerpt from global lock order graph*

This bit of the graph largely relates to networking

Local clusters: e.g., a set of closely related locks from the **pf** firewall; two are leaf nodes; one is held over calls to another subsystem

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 in the system, since almost all components depend on memory allocation



* Turns out that local lock order is pretty complicated too

WITNESS debug output

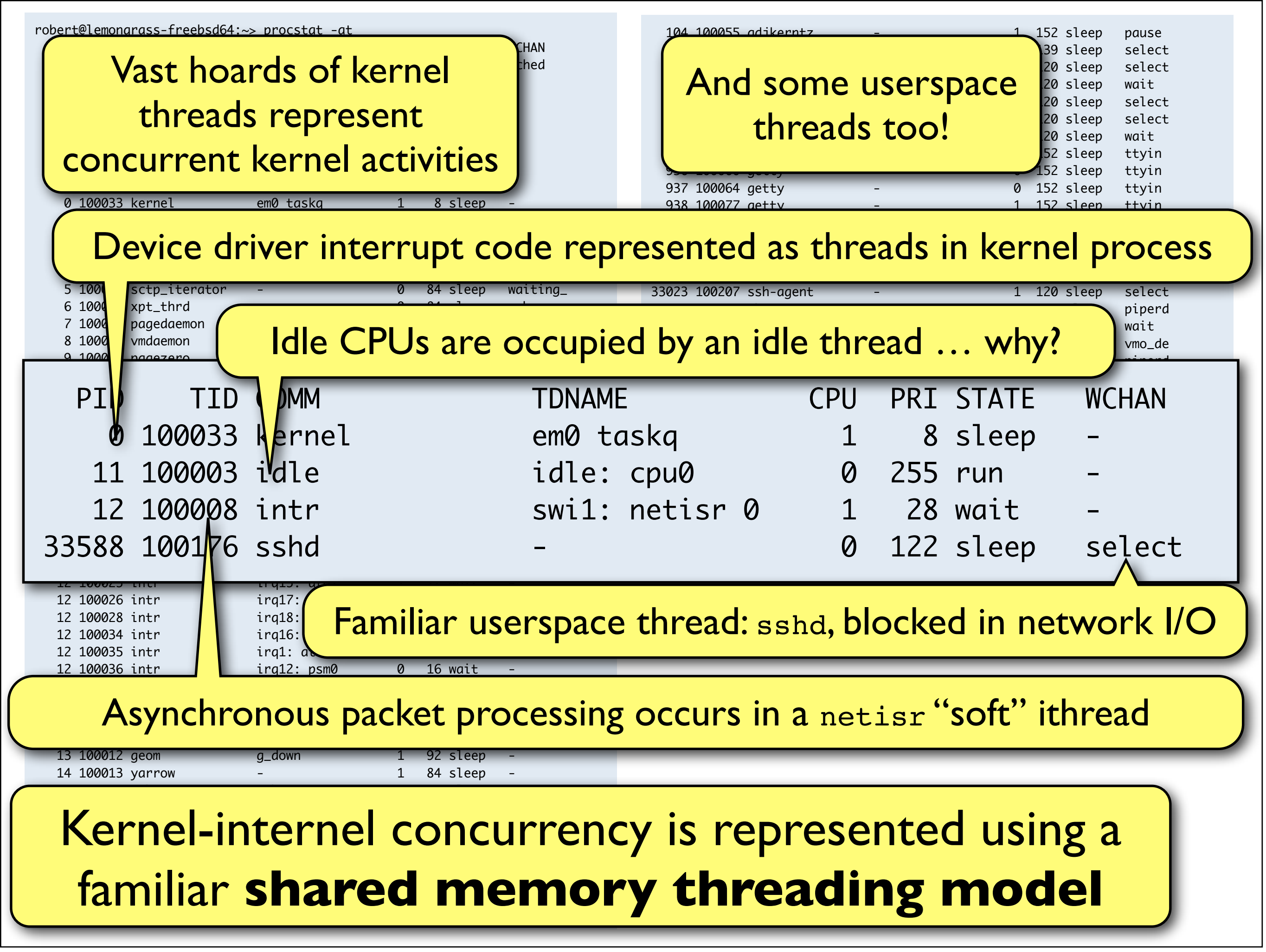
```
1st 0xffffff80025207f0 run0_node_lock (run0_node_lock) @ /usr/src/sys/net80211/ieee80211_ioctl.c:1341
 2nd 0xffffff80025142a8 run0 (network driver) @ /usr/src/sys/modules/usb/run/../../../dev/usb/wlan/
if_run.c:3368
KDB: stack backtrace:
db_trace_self_wrapper() at db_trace_self_wrapper+0x2a
kdb_backtrace() 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 two acquisitions

Stack trace to acquisition that triggered cycle

So how is all this used?

- Kernel is heavily multi-threaded
- Each user thread has a corresponding kernel thread
  - Represents user thread when in syscall, page fault, etc.
- Many kernel services rely on/execute in asynchronous threads
  - Interrupts, timers, I/O, networking, etc.
- Therefore extensive synchronisation
  - Locking model is almost always *data-oriented*
  - Think *monitors* rather than *critical sections*
  - Reference counting or reader-writer locks used for stability



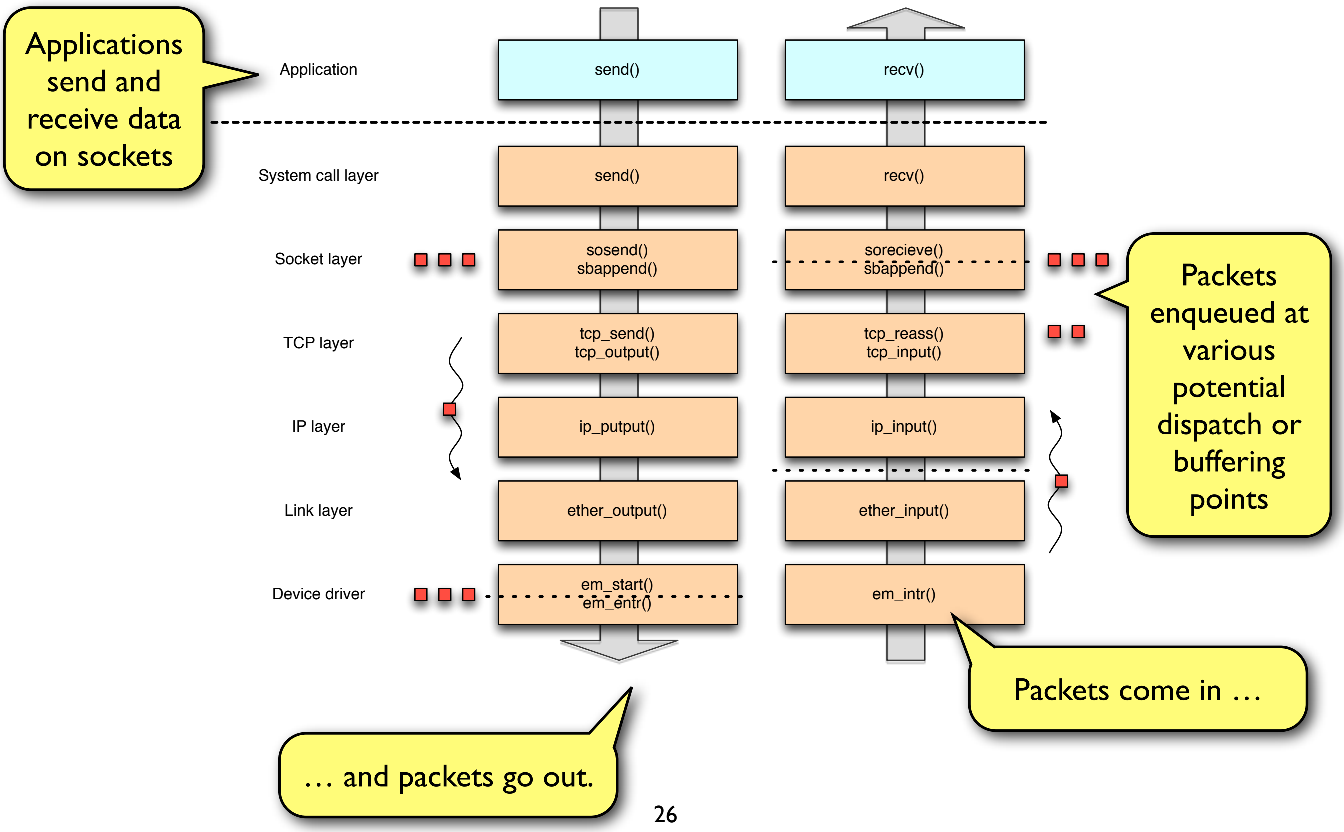
Case study: network stack

- First, make it safe without the Giant lock
  - Lots of data structures require locks
  - Process synchronisation already exists but will be added to
  - Establish key work flows, lock orders
- Then, optimise
  - Especially locking primitives themselves
- As hardware becomes more parallel, identify and exploit further concurrency opportunities
  - Add more threads and distributing more work

Network-stack work flow

- Don't need to understand details of networking:
  - Applications send and receive data on sockets
  - Packets go in and out of network interface
  - The middle bit of that picture is full of *layers*
- Processing occurs in *layers*: decapsulation, lookup, reassembly, ...
  - Layers are sometimes *directly dispatched* and sometimes involve a *producer-consumer queue* to a second thread
  - In latter case, we experience concurrency (even parallelism)
- Send and receive paths also (largely) concurrent

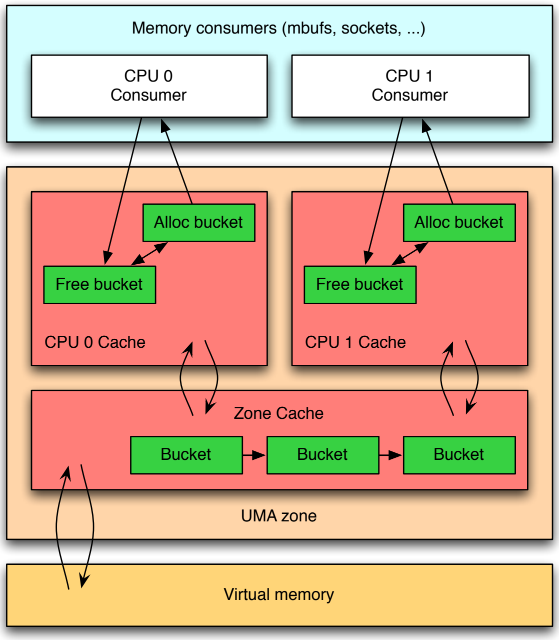
Network stack work flows



What to lock and how? (1)

- Fine-grained locking overhead vs. coarse-grained contention
  - Some contention is inevitable: reflects actual communication
  - Other contention is effectively *false sharing*
- Principle: *data locks* rather than *critical sections*
  - Key structures: network interfaces, sockets, work queues
  - Independent instances should be parallelisable
- Different locks at different layers (sockets vs. control blocks)
- Parallelism at the same layer (receive vs. send socket buffers)
- Things not to lock: mbufs ("work")

Example: universal memory allocator (UMA)

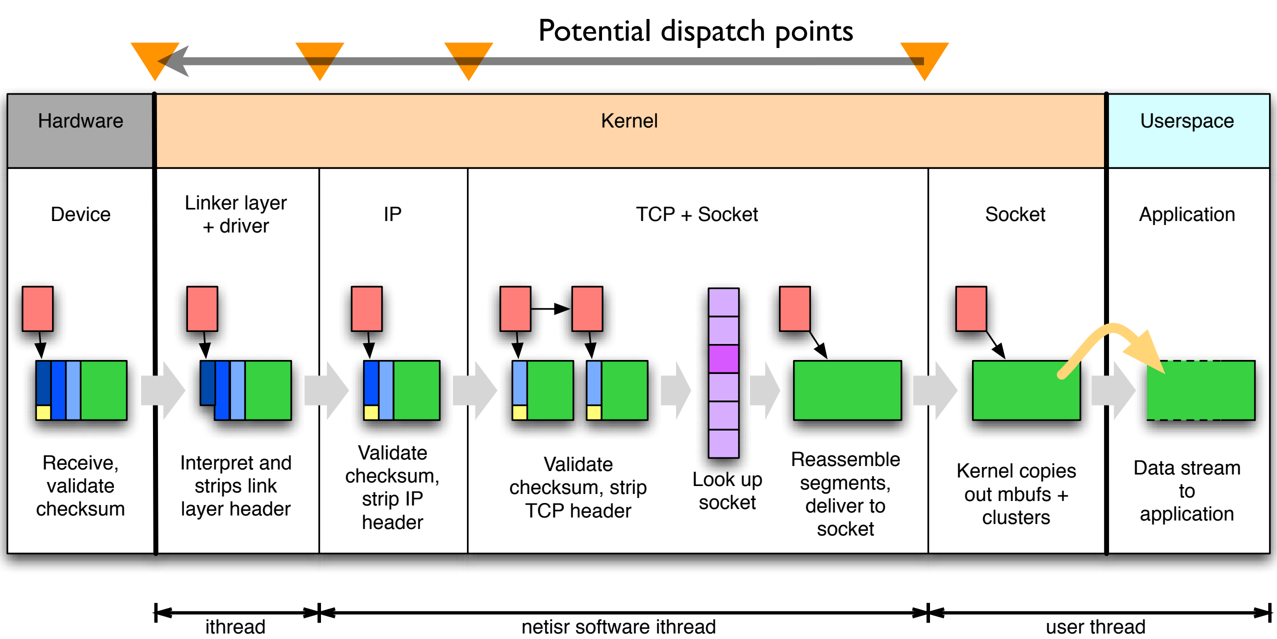


- Key low-level kernel component
- Slab allocator (Bonwick 1994)
- Object-oriented memory model: init/destroy, alloc/free
- Per-CPU caches
  - Protected by critical sections
  - Encourage locality by allocating memory where last freed
  - Avoid zone lock contention

Work distribution

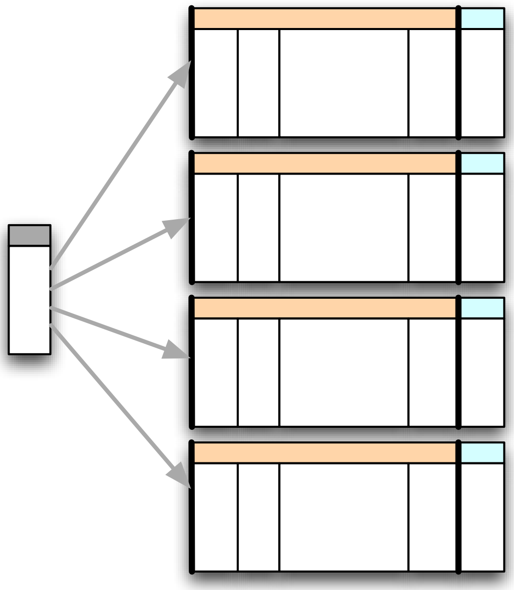
- Packets are units of work
- Parallel work requires distribution to multiple threads
- Must keep packets ordered -- or TCP gets very upset!
- This requires a strong notion of per-flow *serialisation*
  - I.e., no generalised producer-consumer/round robin
- Various strategies to keep work ordered – process in a single thread, or multiple threads linked by a queue, etc.
- Establish flow-CPU affinity – utilise caches well

TCP input path



A more recent trend: multiqueue NICs

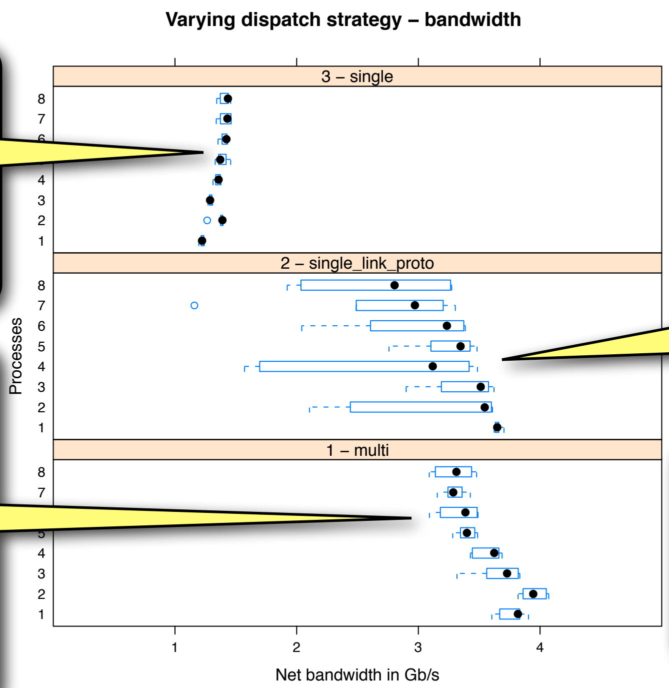
- Key source of OS contention: locks around access to hardware devices
- Parallelism for hardware interface: each NIC has *N* input and output queues
- Flow order maintained by hashing 2- and 4-tuples in TCP/IP headers
- Each input queue assigned its own thread to process



Complex interactions between scheduling and work

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

Hardware work distribution to multiple threads is a little higher, but more importantly, has lower variance



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

Notice shapes of curves: parallelism helps, but saturation hurts

Changes in hardware motivate changes in concurrency strategy

- 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

Longer-term strategies

- Optimise for contention: communication is inevitable
- Increase use of lockless primitives: e.g., stats, queues
- Use optimistic techniques for infrequent writes: rmlocks
- Replicate data structures; perhaps with weak consistency
  - E.g., per-CPU statistics, per-CPU memory caches
- Use distribution/affinity strategies minimising contention
- Address not just parallelism, but NUMA and I/O affinity

Conclusion

- FreeBSD employs many of techniques we've discussed
  - Mutual exclusion, process synchronisation
  - Producer-consumer
  - Lockless primitives
  - Transaction-like notions − e.g., file system journaling
- But real-world systems are **really** complicated
  - Hopefully you will mostly consume, rather than produce, concurrency primitives like these
- See you in distributed systems!