6.828 2014 Lecture 17: Scalable Locks

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Plan:
  cost of spinlocks -- non-scalable
  effect on real systems
  scalable locks

Why this topic?
  Figure 2 in the paper -- disaster! (details later)
  the locks themselves are ruining performance
    rather than letting us harness multi-core to improve performance
  this "non-scalable lock" phenomenon is important
  why it happens is interesting and worth understanding
  the solutions are clever exercises in parallel programming

the problem is interaction of locks w/ multi-core caching
  so let's look at the details

back in the locking lecture, we had a fairly simple model of multiple cores
  cores, shared bus, RAM
  to implement acquire, x86's xchg instruction locked the bus
    provided atomicity for xchg

real computers are much more complex
  bus, RAM quite slow compared to core speed
  per-core cache to compensate
  hit: a few cycles
  RAM: 100s of cycles

how to ensure caches aren't stale?
  core 1 reads+caches x=10, core 2 writes x=11, core 1 reads x=?

answer:
  "cache coherence protocol"
  ensures that each read sees the latest write
    actually more subtle; look up "sequential consistency"

how does cache coherence work?
  many schemes, here's a simple one
  each cache line: state, address, 64 bytes of data
  states: Modified, Shared, Invalid [MSI]
  cores exchange messages as they read and write

messages (much simplified)
  invalidate(addr): delete from your cache
  find(addr): does any core have a copy?
  all msgs are broadcast to all cores

how do the cores coordinate with each other?
  I + local read -> find, S
  I + local write -> find, inval, M
  S + local read -> S
  S + local write -> inval, M
  S + recv inval -> I
  S + recv find  -> nothing, S
  M + recv inval -> I
  M + recv find  -> reply, S

can read w/o bus traffic if already S
can write w/o bus traffic if already M
  "write-back"

compatibility of states between 2 cores:
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		core1		
		M	S	I
	M	-	-	+
core2	S	-	+	+
	I	+	+	+

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invariant: for each line, at most one core in M
invariant: for each line, either one M or many S, never both

Q: what patterns of use benefit from this coherence scheme?
   read-only data (every cache can have a copy)
   data written multiple times by one core (M gives exclusive use, cheap writes)

other plans are possible
  e.g. writes update copies rather than invalidating
  but "write-invalidate" seems generally the best

Real hardware uses much more clever schemes
  mesh of links instead of bus; unicast instead of broadcast
    "interconnect"
  distributed directory to track which cores cache each line
    unicast find to directory

Q: why do we need locks if we have cache coherence?
   cache coherence ensures that cores read fresh data
   locks avoid lost updates in read-modify-write cycles
     and prevent anyone from seeing partially updated data structures

people build locks from h/w-supported atomic instructions
  xv6 uses atomic exchange
  other locks use test-and-set, atomic increment, &c
  the __sync_... functions in the handout turn into atomic instructions

how does the hardware implement atomic instructions?
  get the line in M mode
  defer coherence msgs
  do all the steps (e.g. read old value, write new value)
  resume processing msgs

what is performance of locks?
  assume N cores are waiting for the lock
  how long does it take to hand off the lock?
    from previous holder to next holder
  bottleneck is usually the interconnect
    so we'll measure cost in terms of # of msgs

what performance could we hope for?
  if N cores waiting,
  get through them all in O(N) time
  so each critical section and handoff takes O(1) time
    i.e. does not increase with N

test&set spinlock (xv6/jos)
  waiting cores repeatedly execute e.g. atomic exchange
  Q: is that a problem?
  yes!
    we don't care if waiting cores waste their own time
    we do care if waiting cores slow lock holder!
  time for critical section and release:
    holder must wait in line for access to bus
    so holder's mem ops take O(N) time
    so handoff time takes O(N)

Q: is O(N) handoff time a problem?
   yes! we wanted O(1) time
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    O(N) per handoff means all N cores takes O(N^2) time, not O(N)

ticket locks (linux):
  goal: read-only spin loop, rather than repeated atomic instruction
  goal: fairness (turns out t-s locks aren't fair)
  idea: assign numbers, wake up one at a time
    avoid constant t-s atomic instructions by waiters
  Q: why is it cheaper than t-s lock?
  Q: why is it fair?
  time analysis:
    what happens in acquire?
      atomic increment -- O(1) broadcast msg
        just once, not repeated
      then read-only spin, no cost until next release
    what happens after release?
      invalidate msg for now_serving
      N "find" msgs for each core to read now_serving
    so handoff has cost O(N)
    note: it was *reading* that was costly!
  oops, just as bad O() cost as test-and-set

jargon: test-and-set and ticket locks are "non-scalable" locks
  == cost of single handoff increases with N

is the cost of non-scalable locks a serious problem?
  after all, programs do lots of other things than locking
  maybe locking cost is tiny compared to other stuff

see paper's Figure 2
  let's consider Figure 2(c), PFIND -- parallel find
  x-axis is # of cores, y-axis is finds completed per second (total throughput)
  why does it go up?
  why does it level off?
  why does it go *down*?
  what governs how far up it goes -- i.e. the max throughput?
  why does it go down so steeply?

reason for suddenness of collapse
  serial section takes 7% on one core (Figure 3, last column)
  so w/ 14 cores you'd expect just one or two in crit section
  so it seems odd that collapse happens so soon
  BUT:
    once P(two cores waiting for lock) is substantial,
    critical section + handoff starts taking longer
    so starts to be more than 7%
    so more cores end up waiting
    so N grows, and thus handoff time, and thus N...

some perspective
  acquire(l)
  x++
  release(l)
  surely a critical section this short cannot affect overall performance?
  takes a few dozen cycles if same core last held the lock (still in M)
    everything operates out of the cache, very fast
  a hundred if lock not held, some other core previously held
  10,000 if contended by dozens of cores
  many kernel operations only take a few 100 cycles total
    so a contended lock may increase cost not by a few percent
    but by 100x!

how to make locks scale well?
  we want just O(1) msgs during a release
  how to cause only one core to read/write lock after a release?
  how to wake up just one core at a time?
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test-and-set with exponential backoff (t_s_exp_acquire):
  goal: avoid everyone jumping in at once
    space out attempts to acquire lock
    simultaneous attempts were reason for O(N) release time w/ t-s
    if total rate of tries is low, only one core will attempt per release
  why not constant delay?
    each core re-tries after random delay with constant average
    hard to choose delay time
    too large: waste
    too small: all N cores probe mult times/crit, so O(N) release time
  why exponential backoff?
    i.e. why start with small delay, double it?
    try to get lucky at first (maybe only a few cores attempting)
    doubling means takes only a few attempts until delay >= N * crit section
      i.e. just one attempt per release
  illustration:
    eventually will be roughly one probe per critical section time
    then all will complete in that backoff round
  can we analyze # of probes?
    not that easy
    suppose takes time O(N) for all cores to succeed
    how many probes does each core make in time N? logN
    so total probes: N*logN
    so cost per release: O(logN)
    not O(1), but much better than O(N)
  problem: unlikely to be fair!
    some cores will have much lower delays than others
    will win, and come back, and win again
    some cores will have huge delays, will sit idle
      doing no harm, but doing no work

anderson:
  goal: O(1) release time, and fair
  what if each core spins on a *different* cache line?
  acquire cost?
    atomic increment, then read-only spin
  release cost?
    invalidate next holder's slots[]
    only they have to re-load
    no other cores involved
  so O(1) per release -- victory!
  problem: high space cost
    N slots per lock
    often much more than size of protected object

MCS
  [just diagram, no code]
  goal: as scalable as anderson, but less space used
  idea: linked list of waiters per lock
  idea: one list element per thread, since a thread can wait on only one lock
    so total space is O(locks + threads), not anderson't O(locks*threads)
  acquire() pushes caller's element at end of list
    caller then spins on a variable in its own element
  release() wakes up next element, pops its own element
  change in API (need to pass qnode to acquire and release to qnode allocation)

performance of scalable locks?
  figure 10 shows ticket, MCS, and optimized backoff
  # cores on x-axis, total throughput on y-axis
  benchmark acquires and releases, critical section dirties four cache lines
  Q: why doesn't throughput go up as you add more cores?
  ticket is best on two cores -- just one atomic instruction
  ticket scales badly: cost goes up with more cores
  MCS scales well: cost stays the same with more cores
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Figure 11 shows uncontended cost
  very fast if no contention!
  ticket:
    acquire uses a single atomic instruction, so 10s more expensive than release
    some what more expensive if so emother core had it last

Concl.
  use scalable locks
  even better: fix the underlying problem!
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