An Overview of Locking
in the FreeBSD Kernel

Brought to you by

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Outline

- Historic synchronization
- Lock hierarchy
- Turnstiles and sleep queues
- Details of each lock type
- Witness system

Historic Synchronization

1) Check for Resource

2) If NOT Available

   - set WANT flag
   - sleep on it

3) If IS Available

   - set LOCK flag
   - use it (while possibly sleeping)
   - clear LOCK flag
   - if WANT flag set wakeup all processes sleeping on it

Lock Hierarchy

- Hardware − memory interlock test-and-set
- Spin mutex − spin lock
- Locks that block briefly, but may not sleep
  - Blocking mutex − spin for a while, then block on a turnstile
  - Pool mutex − general-use blocking mutex
  - Reader-Writer locks − mutexes with shared-exclusive semantics
  - Read-mostly locks − fast access for reading
- Locks using sleep-queue interface
  - Shared-Exclusive locks − fast and simple sleep locks
  - Condition variables − wrapper on traditional sleep/wakeup
  - Lock manager − long-term full-function sleep lock
- Witness − partially-ordered sleep locks

Turnstiles

- Used by blocking mutexes, reader-writer, and read-mostly locks
- Designed for short periods, typically a few tens of instructions
- Used to protect read and write access to data structures and lists
- May not own a turnstile lock when requesting a sleep-queue lock
- Tracks current lock holder
- Priority propagation from waiter to holder

Turnstile Implementation

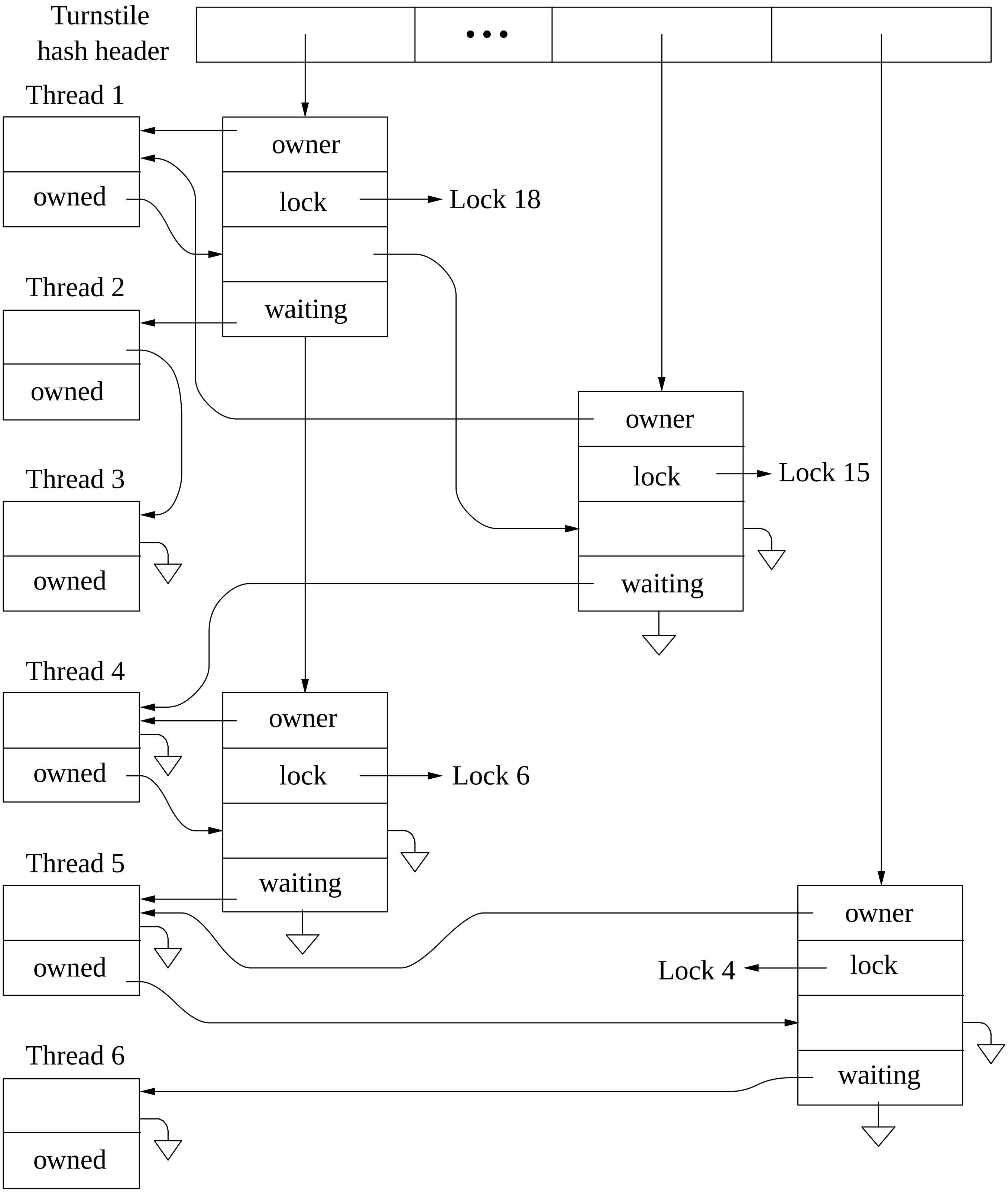
- Hash header to quickly find a lock’s turnstile. The turnstile points to the thread holding the lock and to any threads waiting for the lock

- A turnstile is needed each time a thread blocks. Since a thread can only block on one lock at a time, it provides its own turnstile.

- Unneeded turnstiles are saved and returned when a thread awakens

- If the holder of a lock has a lower priority than the thread about to be blocked, recursively propagate the higher priority to the holder (but only until it releases the lock).

Turnstile Data Structures



Sleep Queues

- Used by shared-exclusive locks, condition variables, and lock-manager locks
- Designed for long periods, typically waiting for I/O events or user input
- No priority propagation
- May not own a turnstile lock when requesting a sleep-queue lock
- Tracks current exclusive lock holder
- May be recursive

Critical Sections

- Uses critical_enter() and critical exit()
- While in a critical section:
  - The thread cannot be preempted by another thread
  - The thread cannot be migrated to another CPU
- Critical sections are much like the old single threaded kernel
- Useful for per-CPU data structures like a run-queue or CPU-specific memory allocation structures
- Cannot protect systemwide data structures

Hardware Requirements for Locking

- Minimum requirement is test-and-set instruction
- On modern hardware, FreeBSD uses compare-and-swap
    - Owner field for a free lock contains MTX_UNOWNED
    - Owner field for a held lock contains pointer to owning thread
    - Allocation attempt compares lock owner with MTX_UNOWNED and if it matches stores pointer to acquiring thread and returns previous owner value
    - If previous owner value was MTX_UNOWNED, acquisition succeeded
- Store MTX_UNOWNED in owner field for lock to release it

Spin Mutex

- Exclusive access only
- Loops waiting for the mutex to become available
- Runs inside a critical section while held to avoid deadlock
- More expensive to obtain than a blocking mutex
- In FreeBSD, used only for low-level scheduling and context-switching

Blocking Mutex

- Exclusive access only

- Uses adaptive spinning which only spins if the owner of the lock is currently running

    - Current owner typically done with it quickly

    - If owner on run queue, blocking lets waiter give its CPU to owner

- All waiters are awakened when lock is released

    - Cheaper to release an uncontested lock since just a store rather than find and traverse the turnstile

    - Often end up scheduling sequentially

    - When scheduled concurrently, adaptive spinning usually ensures that they will not block

Pool Mutex

- Used for small short-lived data structures
  - Just need a pointer to a mutex rather than large mutex itself
  - Mutex is preallocated so avoid high creation and destruction times
- Example is poll system call that needs a structure to track a poll request from the time the system call is entered until the arrival of data for one of the polled descriptors.

Reader-Writer Locks

- In addition to exclusive access of a mutex also provide shared semantics
- Uses a turnstile so cannot be held when thread goes to sleep
- Provides priority propagation for exclusive access
- Does not provide priority propagation for shared access
- May specify permission to recurse

Read-Mostly Locks

- Same properties as reader-writer locks except they add priority propagation for shared access by tracking shared owners using a caller-supplied tracker data structure
- Designed for fast access for readers (shared access) assuming there will be few writers (exclusive access)
  - Read without a lock then check if write happened
  - If write happened fall back to using lock to get coherent access
- The routing table is a good example of a read-mostly data structure
- Best way to implement read-mostly locks is patented by IBM
  - IBM allows GPL’ed code to use their patented implementation at no cost
  - FreeBSD is not GPL, so we have to use a slower technique

Shared-Exclusive Locks

- Fastest and simplest of the locks that can sleep
- Provide shared and exclusive access
- May specify permission to recurse
- May request interruption by a signal
- Limited upgrade and downgrade capabilities
- Like all sleep locks, does not implement priority propagation

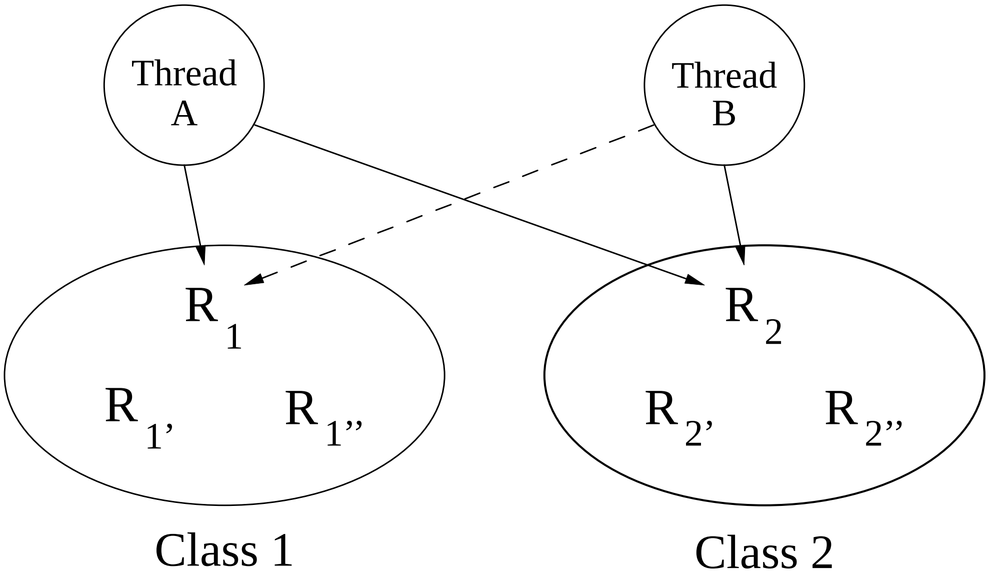
Condition Variables

- Wrapper on traditional sleep and wakeup
- Allows waiting with optional time out and/or interruption by a signal
- Allows waking up one or all waiters
- Must hold a mutex before awakening or waiting (mutex is released while waiting).

Lock Manager Locks

- Most full-featured of the locks that can sleep
- Provide shared and exclusive access
- May specify permission to recurse
- May request a time out and/or interruption by a signal
- Allows downgrade, upgrade, and exclusive upgrade
- The ability to pass ownership of the lock from a thread to the kernel
- The ability to drain all accessing threads in preparation for being deallocated
- Like all sleep locks, does not implement priority propagation

Witness



Partial ordering requires:

1) A thread may acquire only one lock in a class

2) A thread may acquire only a lock in a higher-numbered class than the highest-numbered class for which it already holds a lock

- Programmers can define lock classes
- Witness code observes actual lock ordering and complains when either rule is violated

Questions

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