MULTIPROCESSING AND SYNCHRONIZATION

* Partially Adopted "*Synchronization*, Prof. Erich Nahum"

2017 Operating Systems Design

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Producer

```
while (true) {

      /*  produce an item and put in nextProduced  */
      while (count == BUFFER_SIZE)
            ; // do nothing
         buffer [in] = nextProduced;
         in = (in + 1) % BUFFER_SIZE;
         count++;
}
```

Consumer

```
while (true)  {
        while (count == 0)
              ; // do nothing
              nextConsumed =  buffer[out];
               out = (out + 1) % BUFFER_SIZE;
                 count--;

                /*  consume the item in nextConsumed
}
```

Race Condition

- count++ could be implemented as

  register1 = count
  register1 = register1 + 1
  count = register1

- count-- could be implemented as

  register2 = count
  register2 = register2 - 1
  count = register2

- Consider this execution interleaving with "count = 5" initially:

  S0: producer execute register1 = count {register1 = 5}
  S1: producer execute register1 = register1 + 1 {register1 = 6}
  S2: consumer execute register2 = count {register2 = 5}
  S3: consumer execute register2 = register2 - 1 {register2 = 4}
  S4: producer execute count = register1 {count = 6 }
  S5: consumer execute count = register2 {count = 4}

Need for Synchronization

- When data generated by one process are transferred to another
- When data are shared
- When processes are forced to wait for each other
- When resource usage needs to be coordinated

Kernel Synchronization

- Can think of the kernel as a server
  - Concurrent requests are possible
  - Synchronization is (usually) required
- Need to avoid race conditions
  - Correctness violated by timing changes
  - Need to identify, secure critical section (mutex)
- Kernel vs. userland synch primitives
  - example: semaphore system call vs. in-kernel semaphore
- Synchronization is complex and subtle
- Hierarchy of primitives
  - lowest level: hardware primitives
  - higher level: built using lower-level
    - e.g. semaphores use atomic inc, spinlocks, waitqueues

Linux Synch Primitives

- Memory barriers
  - Avoids compiler, cpu instruction re-ordering
- Atomic operations
  - Memory bus lock, read-modify-write ops
- Interrupt/softirq disabling/enabling
  - Local, global
- Spin locks
  - General, read/write, big reader
- Semaphores
  - General, read/write

Choosing Synch Primitives

- Generally, choice is affected by
  - Will contention be high?
  - Are you in process context?
  - How much do you need to do inside of critical section?
  - Do you need to sleep?
  - Do you need to acquire lock frequently?

Choosing Synch Primitives

- Avoid synch if possible! (clever instruction ordering)
  - Example: inserting in linked list (needs barrier still)
- Use atomics or rw spinlocks if possible
- Use semaphores if you need to sleep
  - Can't sleep in interrupt context
  - Don't sleep holding a spinlock!
- Complicated matrix of choices for protecting data structures accessed by deferred functions

Architectural Dependence

- The implementation of the synchronization primitives is extremely architecture dependent
- This is because only the hardware can guarantee atomicity of an operation
- Each architecture must provide a mechanism for doing an operation that can examine and modify a storage location atomically
- Some architectures do not guarantee atomicity, but inform whether the operation attempted was atomic

Barriers: Motivation

- The compiler can:
  - Reorder code as long as it correctly maintains data flow dependencies within a function and with called functions
  - Reorder the *execution* of code to optimize performance
- The processor can:
  - Reorder instruction execution as long as it correctly maintains register flow dependencies
  - Reorder memory modification as long as it correctly maintains data flow dependencies
  - Reorder the execution of instructions (for performance optimization)

Barriers: Definition

- Barriers are used to *prevent* a processor and/or the compiler from reordering instruction execution and memory modification.
- Barriers are instructions to hardware and/or compiler to complete all pending accesses before issuing any more
  - read memory barrier – acts on read requests
  - write memory barrier – acts on write requests
- Intel –
  - certain instructions act as barriers: lock, iret, control regs
  - rmb – asm volatile("lock;addl $0,0(%%esp)":::"memory")
    - add 0 to top of stack with lock prefix
  - wmb – Intel never re-orders writes, just for compiler

Barrier Operations

- *barrier* – prevent only compiler reordering
- *mb* – prevents load and store reordering
- *rmb* – prevents load reordering
- *wmb* – prevents store reordering
- *smp_mb* – prevent load and store reordering only in SMP kernel
- *smp_rmb* – prevent load reordering only in SMP kernels
- *smp_wmb* – prevent store reordering only in SMP kernels
- *set_mb* – performs assignment and prevents load and store reordering

Serializing with Interrupts

- Basic primitive in original UNIX
- Doesn't protect against other CPUs
- Intel: "interrupts enabled bit"
  - cli to clear (disable), sti to set (enable)
- Enabling is often wrong; need to restore
  - local_irq_save()
  - local_irq_restore()

Interrupt Operations

- Services used to serialize with interrupts are:
  - *local_irq_disable* - disables interrupts on the current CPU
  - *local_irq_enable* - enable interrupts on the current CPU
  - *local_save_flags* - return the interrupt state of the processor
  - *local_restore_flags* - restore the interrupt state of the processor
- Dealing with the full interrupt state of the system is officially discouraged. Locks should be used.

Disabling Deferred Functions

- Disabling interrupts disables deferred functions
- Possible to disable deferred functions but not all interrupts
- Operations (macros):
  - `local_bh_disable()`
  - `local_bh_enable()`

Atomic Operations

- Many instructions not atomic in hardware (smp)
  - Read-modify-write instructions: inc, test-and-set, swap
  - Unaligned memory access
- Compiler may not generate atomic code
  - Even i++ is not necessarily atomic!
- If the data that must be protected is a single word, atomic operations can be used
  - These functions examine and modify the word atomically
- The atomic data type is **`atomic_t`**

Atomic Operations

- Execute in a single instruction
- Can be used in or out of process context (i.e., softirqs)
- Never sleep
- Don't suspend interrupts

Atomic Operations

- *ATOMIC_INIT* – initialize an *atomic_t* variable
- *atomic_read* – examine value atomically
- *atomic_set* – change value atomically
- *atomic_inc* – increment value atomically
- *atomic_dec* – decrement value atomically
- *atomic_add* - add to value atomically
- *atomic_sub* – subtract from value atomically
- *atomic_inc_and_test* – increment value and test for zero
- *atomic_dec_and_test* – decrement value and test for zero
- *atomic_sub_and_test* – subtract from value and test for zero
- *atomic_set_mask* – mask bits atomically
- *atomic_clear_mask* – clear bits atomically

Spin Locks

- A spin lock is a data structure (*spinlock_t*) that is used to synchronize access to critical sections
- Only one thread can be holding a spin lock at any moment. All other threads trying to get the lock will "spin" (loop while checking the lock status)
- Spin locks should not be held for long periods because waiting tasks on other CPUs are spinning, and thus wasting CPU execution time

Spin Lock Operations

- Functions used to work with spin locks:
  - *spin_lock_init* – initialize a spin lock before using it for the first time
  - *spin_lock* – acquire a spin lock, spin waiting if it is not available
  - *spin_unlock* – release a spin lock
  - *spin_unlock_wait* – spin waiting for spin lock to become available, but don't acquire it
  - *spin_trylock* – acquire a spin lock if it is currently free, otherwise return error
  - *spin_is_locked* – return spin lock state

Spin Locks & Interrupts

- The spin lock services also provide interfaces that serialize with interrupts (on the current processor):
  - *spin_lock_irq* - acquire spin lock and disable interrupts
  - *spin_unlock_irq* - release spin lock and reenable
  - *spin_lock_irqsave* - acquire spin lock, save interrupt state, and disable
  - *spin_unlock_irqrestore* - release spin lock and restore interrupt state

RW Spin Locks

- A read/write spin lock is a data structure that allows multiple tasks to hold it in "read" state or one task to hold it in "write" state (but not both conditions at the same time)
- This is convenient when multiple tasks wish to examine a data structure, but don't want to see it in an inconsistent state
- A lock may not be held in read state when requesting it for write state
- The data type for a read/write spin lock is *rwlock_t*
- Writers can starve waiting behind readers

RW Spin Lock Operations

- Several functions are used to work with read/write spin locks:
  - *rwlock_init* – initialize a read/write lock before using it for the first time
  - *read_lock* – get a read/write lock for read
  - *write_lock* – get a read/write lock for write
  - *read_unlock* – release a read/write lock that was held for read
  - *write_unlock* – release a read/write lock that was held for write
  - *read_trylock, write_trylock* – acquire a read/write lock if it is currently free, otherwise return error

RW Spin Locks & Interrupts

- The read/write lock services also provide interfaces that serialize with interrupts (on the current processor):
  - *read_lock_irq* - acquire lock for read and disable interrupts
  - *read_unlock_irq* - release read lock and reenable
  - *read_lock_irqsave* - acquire lock for read, save interrupt state, and disable
  - *read_unlock_irqrestore* - release read lock and restore interrupt state
- Corresponding functions for write exist as well (e.g., *write_lock_irqsave*)

Semaphores

- A *semaphore* is a data structure that is used to synchronize access to critical sections or other resources
- A *semaphore* allows a fixed number of tasks (generally one for critical sections) to "hold" the semaphore at one time. Any more tasks requesting to hold the *semaphore* are blocked (put to sleep)
- A *semaphore* can be used for serialization only in code that is allowed to block

Semaphore Operations

- Operations for manipulating semaphores:
  - *up* – release the semaphore
  - *down* – get the semaphore (can block)
  - *down_interruptible* – get the semaphore, but return whether we blocked
  - *down_trylock* – try to get the semaphore without blocking, otherwise return an error

Semaphores

- optimized assembly code for normal case (down())
  - C code for slower "contended" case (__down())
- up() is easy
  - atomically increment; wake_up() if necessary
- uncontended down() is easy
  - atomically decrement; continue
- contended down() is really complex!
  - basically increment sleepers and sleep
  - loop because of potentially concurrent ups/downs
- still in down() path when lock is acquired

RW Semaphores

- A *rw_semaphore* is a semaphore that allows either one writer or any number of readers (but not both at the same time) to hold it.
- Any writer requesting to hold the *rw_semaphore* is blocked when there are readers holding it.
- A *rw_semaphore* can be used for serialization only in code that is allowed to block. Both types of semaphores are the only synchronization objects that should be held when blocking.
- Writers will not starve: once a writer arrives, readers queue behind it
- Increases concurrency; introduced in 2.4

RW Semaphore Operations

- Operations for manipulating semaphores:

  up_read – release a *rw_semaphore* held for read.

  up_write – release a *rw_semaphore* held for write.

  down_read – get a *rw_semaphore* for read (can block, if a writer is holding it)

  down_write – get a *rw_semaphore* for write (can block, if one or more readers are holding it)

More RW Semaphore Ops

- Operations for manipulating semaphores:
  - *down_read_trylock* – try to get a *rw_semaphore* for read without blocking, otherwise return an error
  - *down_write_trylock* – try to get a *rw_semaphore* for write without blocking, otherwise return an error
  - *downgrade_write* – atomically release a *rw_semaphore* for write and acquire it for read (can't block)

Mutexes

- A *mutex* is a data structure that is *also* used to synchronize access to critical sections or other resources, introduced in 2.6.16.
- Core difference: only 1 owner, while semaphores can have multiple owners
- Historically, semaphores have been used in the kernel, but now mutexes are encouraged, unless counting feature is really required
- As of 2.6.26, major effort to eliminate semaphores completely, and may eventually disappear
- Replace remaining instances with *completions*

Why Mutexes?

`Documentation/mutex-design.txt`

- Pros
  - Simpler (lighter weight)
  - Tighter code
  - Slightly faster, better scalability
  - No fastpath tradeoffs
  - Debug support – strict checking of adhering to semantics (if compiled in)
- Cons
  - Not the same as semaphores
  - Cannot be used from interrupt context
  - Owner must release

Mutex Operations

- Operations for manipulating mutexes:

  mutex_unlock – release the mutex

  mutex_lock – get the mutex (can block)

  mutex_lock_interruptible – get the mutex, but allow interrupts

  mutex_trylock – try to get the mutex without blocking, otherwise return an error

  mutex_is_locked – determine if mutex is locked

Real-Time Mutexes

- Implement priority inheritance to solve priority inversion
- `task_struct->prio` will be adjusted to the highest of priorities of waiters
- `task_struct->prio` will be set back to its normal priority

Completions

- Higher-level means of waiting for events
- Optimized for contended case

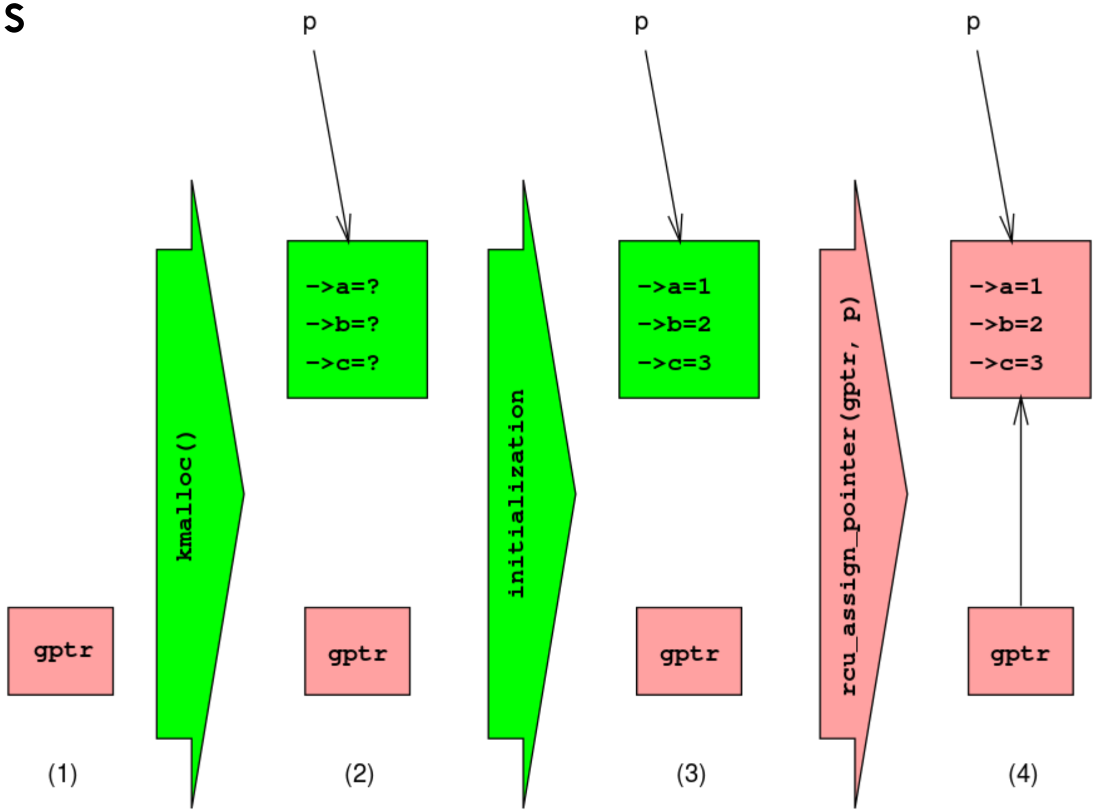
init_completion // replaces sema_init
complete // replaces up
wait_for_completion // replaces down
wait_for_completion_interruptible
wait_for_completion_timeout
wait_for_completion_interruptable_timeout

The Big Kernel Lock (BKL)

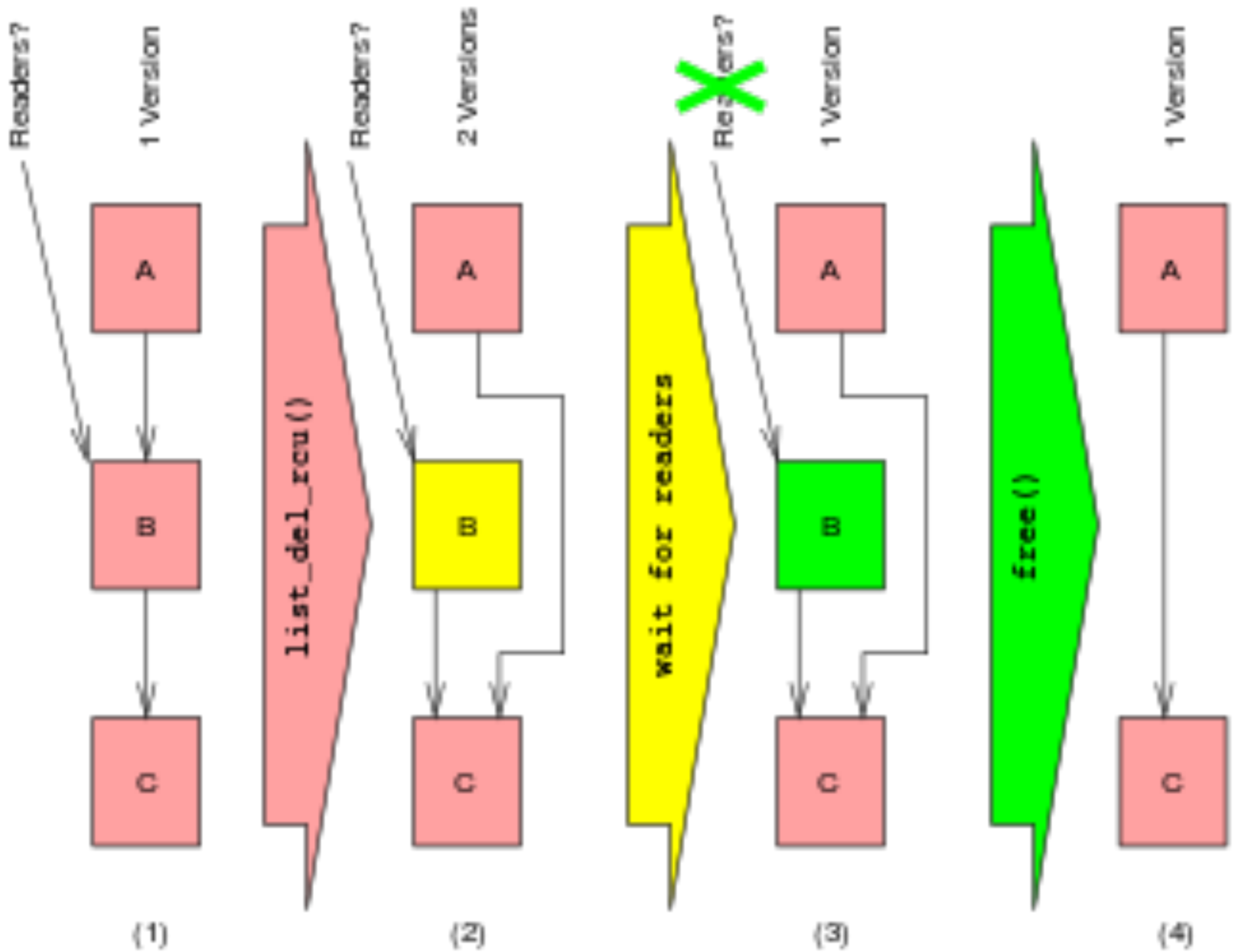
- For serialization that is not performance sensitive, the big kernel lock (BKL) was used
  - This mechanism is historical and should generally be avoided.
  - The function *lock_kernel* gets the big kernel lock.
  - The function *unlock_kernel* releases the big kernel lock.
  - The function *kernel_locked* returns whether the kernel lock is currently held by the current task.
  - The big kernel lock itself is a simple lock called *kernel_flag*.

Read-Copy-Update Locks

- RCU is an alternative to a readers-writer lock
  - Extremely low overhead
  - Wait-free reads



Read-Copy-Update Locks



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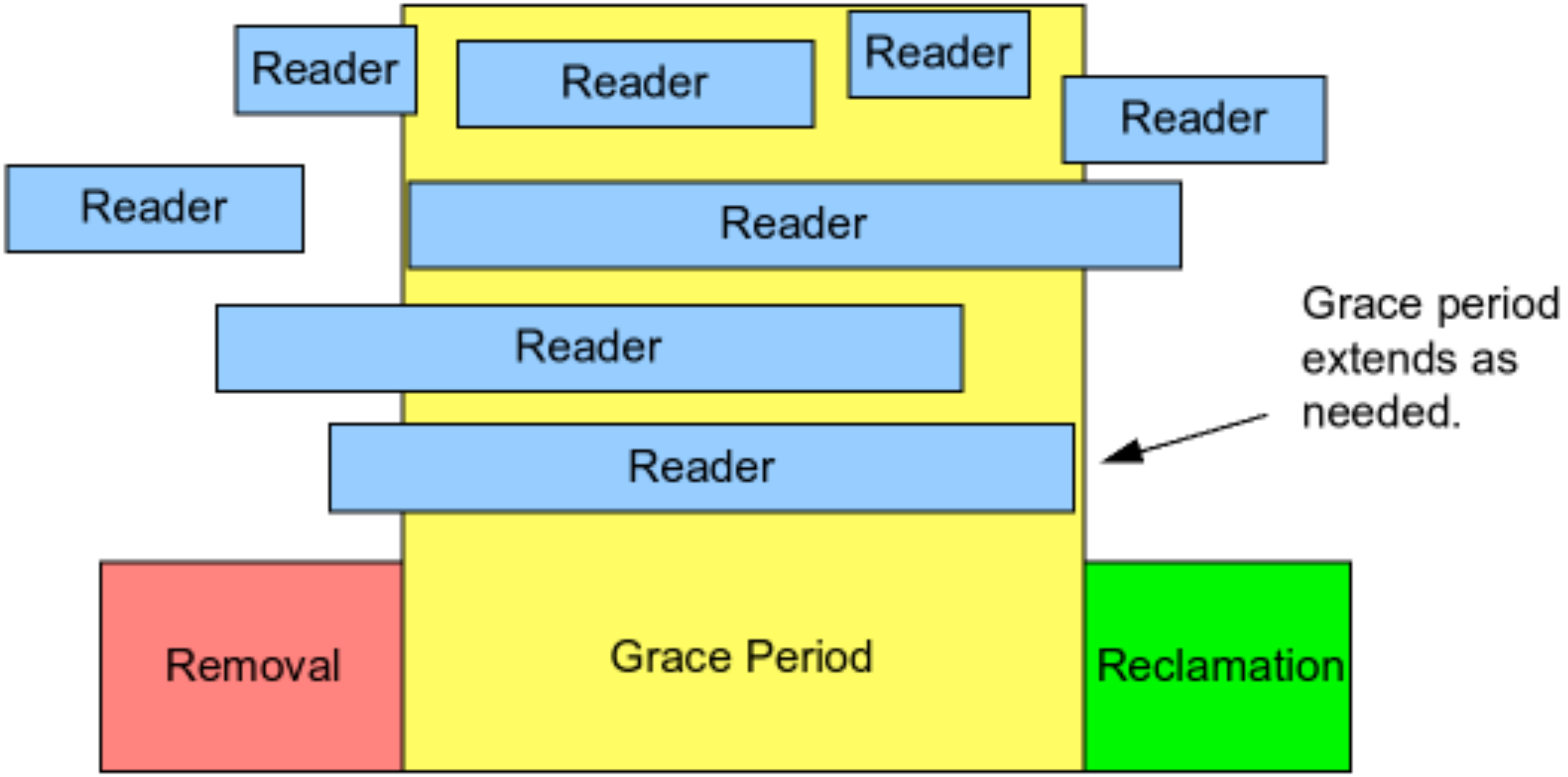

Read-Copy-Update Locks