Locking

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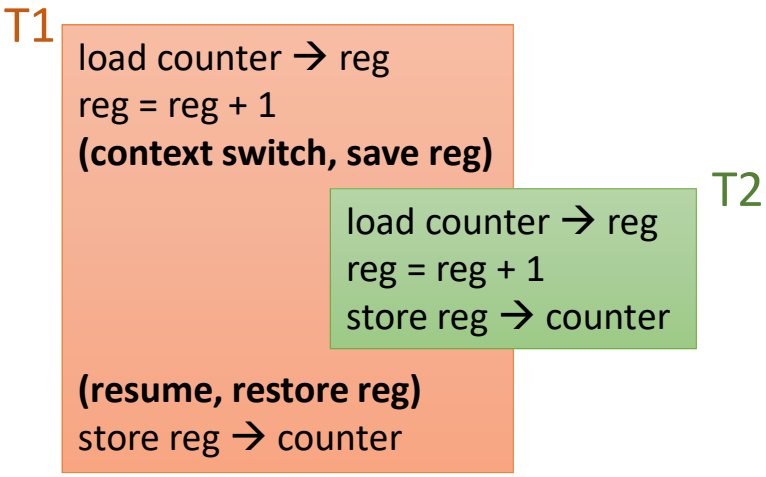
Recap: Shared data access in threads

load counter → reg
reg = reg + 1
store reg → counter

- The C code “counter = counter + 1” is compiled into multiple instructions
  - Load counter variable from memory into register
  - Increment register
  - Store register back into memory of counter variable
- What happens when two threads run this line of code concurrently?

  - Counter is 0 initially
  - T1 loads counter into register, increment reg
  - Context switch, register (value 1) saved
  - T2 runs, loads counter 0 from memory
  - T2 increments register, stores to memory
  - T1 resumes, stores register value to counter
  - Counter value rewritten to 1 again
  - Final counter value is 1, expected value is 2

  Both threads updated the value, not consecutively but concurrently leading to unexpected result.



Recap: Race conditions, critical sections

- Incorrect execution of code due to concurrency is called race condition
  - Due to unfortunate timing of context switches, atomicity of data update violated
- Race conditions happen when we have concurrent execution on shared data
  - Threads sharing common data in memory image of user processes
  - Processes in kernel mode sharing OS data structures
- We require mutual exclusion on some parts of user or OS code
  - Concurrent execution by multiple threads/processes should not be permitted
- Parts of program that need to be executed with mutual exclusion for correct operation are called critical sections
  - Present in multi-threaded programs, OS code
- How to access critical sections with mutual exclusion? Using locks

Using locks

- Locks are special variables that provide mutual exclusion
  - Provided by threading libraries
  - Can call lock/acquire and unlock/release functions on a lock
- When a thread T1 acquires a lock, another thread T2 cannot acquire same lock
  - Execution of T2 stops at the lock statement
  - T2 can proceed only after T1 releases the lock
- Acquire lock → critical section → release lock ensures mutual exclusion in critical section

```
int counter;
pthread_mutex_t m;

void start_fn() {

   for(int i=0; i < 1000; i++) {
      pthread_mutex_lock(&m)
      counter = counter + 1
      pthread_mutex_unlock(&m)
}

main() {
   counter = 0

   pthread_t t1, t2
   pthread_create(&t1,..,  start_fn, ..)
   pthread_create(&t2, .., start_fn,..)

   pthread_join(t1, ..)
   pthread_join(t2, ..)

   print counter
}
```

How to implement a lock?

- Goals of a lock implementation
  - Mutual exclusion (obviously!)
  - Fairness: all threads should eventually get the lock, and no thread should starve
  - Low overhead: acquiring, releasing, and waiting for lock should not consume too many resources
- Implementation of locks are needed for both userspace programs (e.g., pthreads library) and kernel code
  - Separate implementations in user libraries and OS

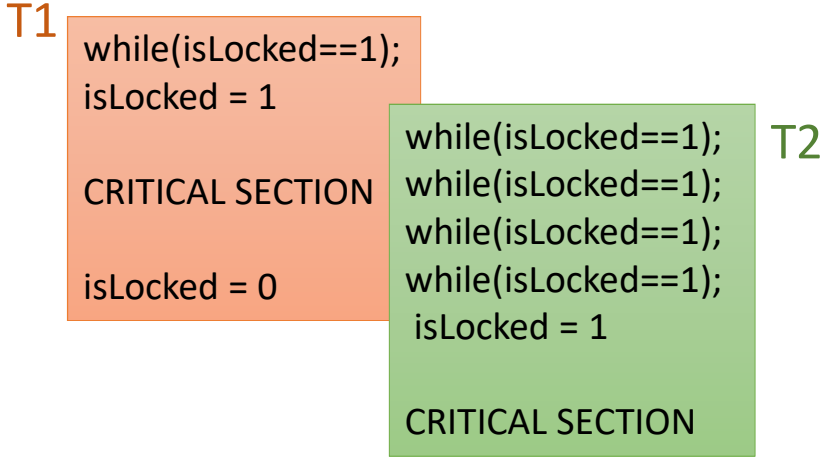
Incorrect lock implementation

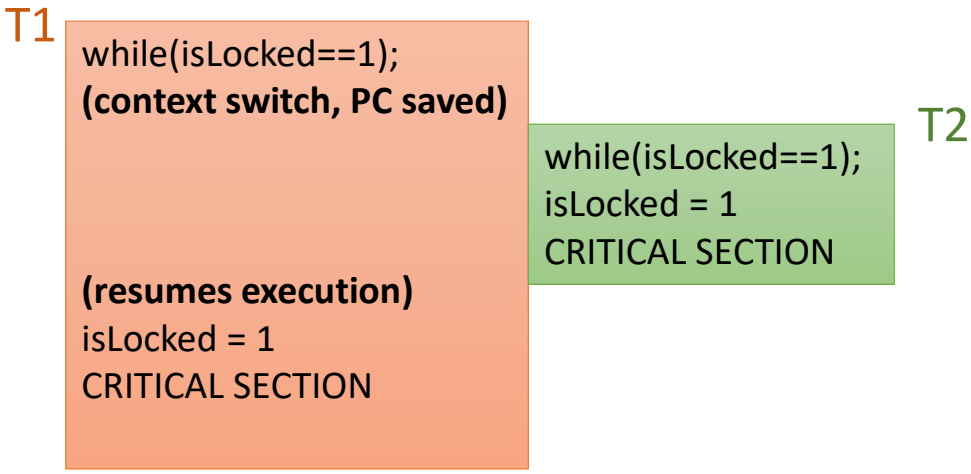
- Example of incorrect lock implementation
  - Use variable isLocked to indicate lock status (0 means lock is free, 1 indicates it is acquired)
  - To acquire lock, a thread waits as long as lock is busy, and then sets it to 1 (acquired)
  - One interleaving of executions (left) works while another (right) may not work

```
int isLocked = 0

void acquire_lock() {
   while(isLocked == 1); //wait
   isLocked = 1
}

void release_lock() {
    isLocked = 0
}
```





Hardware atomic instructions

- Need a way to check a variable and set its value atomically
  - No context switch between checking lock variable and setting it
  - But user programs have no control over context switches
- Solution: use hardware atomic instructions
- Example: test-and-set hardware atomic instruction
  - Two arguments: address of variable and new value to set
  - Writes new value into a variable and returns old value in one single step
  - Entire logic implemented in hardware, runs in one single step

```
1       int TestAndSet(int *old_ptr, int new) {
2           int old = *old_ptr; // fetch old value at old_ptr
3           *old_ptr = new;     // store 'new' into old_ptr
4           return old;         // return the old value
5       }
```

Lock implementation using test-and-set

- Simple lock can be implemented using test-and-set instruction
  - isLocked variable indicates lock status (0=free, 1=acquired)
  - If test-and-set(&isLocked, 1) returns 1, it means lock is not free, wait
  - If test-and-set(&isLocked, 1) returns 0, lock was free and was acquired, done!
- No further race conditions possible with this lock implementation
  - All modern lock implementations based on such hardware instructions
  - Software based locking algorithms do not work well in modern systems

```
int isLocked = 0

void acquire_lock() {
   while(test-and-set(&isLocked, 1) == 1); //wait
   //return, lock is acquired
}
```

```
1   typedef struct __lock_t {
2       int flag;
3   } lock_t;
4
5   void init(lock_t *lock) {
6       // 0 indicates that lock is available, 1 that it is held
7       lock->flag = 0;
8   }
9
10  void lock(lock_t *lock) {
11      while (TestAndSet(&lock->flag, 1) == 1)
12          ; // spin-wait (do nothing)
13  }
14
15  void unlock(lock_t *lock) {
16      lock->flag = 0;
17  }
```

Figure 28.3: **A Simple Spin Lock Using Test-and-set**

Image credit: OSTEP

Another instruction: compare-and-swap

- Another example: compare-and-swap (CAS) hardware atomic instruction
  - Three arguments: address of variable, expected old value, new value
  - If variable has expected old value, then write new value and return true; else do not change variable and return false

```
1   int CompareAndSwap(int *ptr, int expected, int new) {
2       int actual = *ptr;
3       if (actual == expected)
4           *ptr = new;
5       return actual;
6   }
```

Figure 28.4: **Compare-and-swap**

Image credit: OSTEP

Lock using CAS

- Lock implementation using compare-and-swap
  - If compare-and-swap(&isLocked, 0, 1) returns false, it means lock is busy, wait
  - If compare-and-swap(&isLocked, 0, 1) returns true, it means old value of lock was 0 and was changed to 1, so lock has been acquired, done!

```
int isLocked = 0

void acquire_lock() {
   while(compare-and-swap(&isLocked, 0, 1) == false); //wait
}
```

Evaluating spinlock implementations

- Correctness: does it lead to mutual exclusion correctly?
- Fairness: are all waiting threads treated fairly? Can we guarantee that every waiting thread will get its turn?
  - The implementations we saw here do not guarantee it
- Performance: overheads of having threads spin for lock
  - Single core system: what happens when thread holding lock is context switched out and other threads that are scheduled continue to spin for lock?
  - Problem less severe in multicore system. Why? (Thread holding lock can finish while other threads are spinning)

Spinlock vs. sleeping mutex

- Simple lock implementation seen here is a spinlock
  - If thread T1 has acquired lock, and thread T2 also wants lock, then T2 will keep spinning in a while loop till lock is free
- Another implementation option: thread can go to sleep (be blocked) while waiting for lock, saving CPU cycles
  - OS blocks waiting thread, context switch to another thread/process
  - Such locks are called (sleeping) mutex
- Threading libraries provide APIs for both spinlocks and sleeping mutex
  - Better to use spinlock if locks are expected to be held for short time, avoid context switch overhead
  - Better to use sleeping mutex if critical sections are long

Guidelines for using locks

- When writing multithreaded programs, careful locking discipline
  - Protect each shared data structure with one lock
  - Locks can be coarse-grained (one big fat lock) or fine-grained (many smaller locks)
  - Any thread wanting to access shared data must acquire corresponding lock before access, release lock after access
- If using third-party libraries in multi-threaded programs, check the documentation to see if if the library is thread-safe
  - Thread-safe implementations work correctly with concurrent access

Guidelines for using locks

- Good practice to acquire locks for both reading and writing data
  - Why locks for reading? We do not want to read incorrect data while another thread is concurrently updating the data
  - Some libraries provide separate locks for reading and writing, allowing multiple threads to concurrently read data if no other thread is writing
- Good practice to minimize use of locks, use only when needed
  - Why? Use of locks serializes thread access, removes gains due to parallelism
  - Example of minimizing lock usage: instead of each thread updating shared global counter, let each thread update a local counter, and periodically update global counter

```
1   typedef struct __counter_t {
2       int             value;
3       pthread_mutex_t lock;
4   } counter_t;
5
6   void init(counter_t *c) {
7       c->value = 0;
8       Pthread_mutex_init(&c->lock, NULL);
9   }
10
11  void increment(counter_t *c) {
12      Pthread_mutex_lock(&c->lock);
13      c->value++;
14      Pthread_mutex_unlock(&c->lock);
15  }
16
17  void decrement(counter_t *c) {
18      Pthread_mutex_lock(&c->lock);
19      c->value--;
20      Pthread_mutex_unlock(&c->lock);
21  }
22
23  int get(counter_t *c) {
24      Pthread_mutex_lock(&c->lock);
25      int rc = c->value;
26      Pthread_mutex_unlock(&c->lock);
27      return rc;
28  }
```

Figure 29.2: **A Counter With Locks**

Image credit: OSTEP

Locking in xv6

- No threads in xv6, no two user programs can access same memory image
  - No need for userspace locks like pthreads mutex
- However, scope for concurrency in xv6 kernel
  - Two processes in kernel mode in different CPUs can access same kernel data structures like ptable
  - Even in single core, when a process is running in kernel mode, another trap occurs, trap handler can access data that was being accessed by previous kernel code
- Solution: spinlocks used to protect critical sections
  - Limit concurrent access to kernel data structures that can result in race conditions
- xv6 also has a sleeping lock (built on spinlock, not discussed)

Spinlocks in xv6

- Acquiring lock: uses xchg x86 atomic instruction (test and set)
  - Atomically set lock variable to new value and returns previous value
  - If previous value is 0, it means free lock has been acquired, success!
  - If previous value is 1, it means lock is held by someone, continue to spin in a busy while loop till success

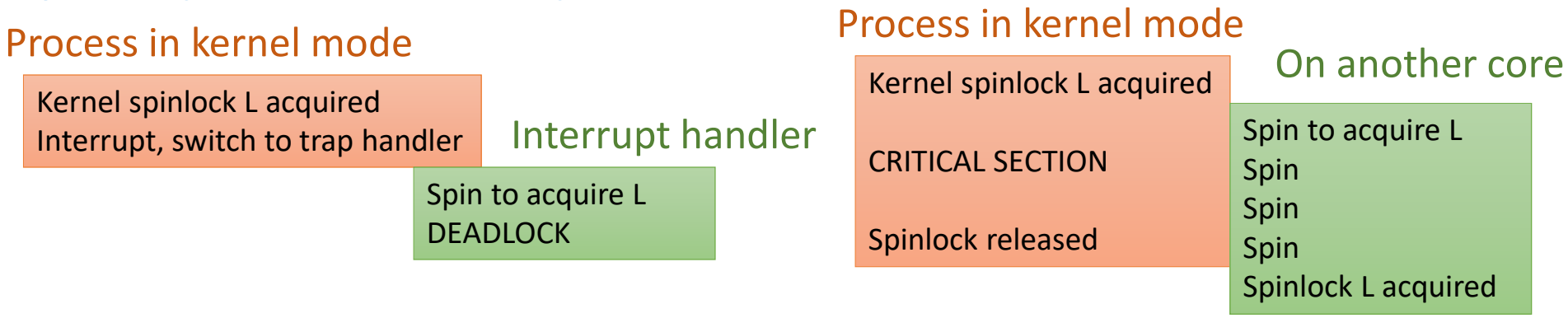
```
1500 // Mutual exclusion lock.
1501 struct spinlock {
1502   uint locked;       // Is the lock held?
1503
1504   // For debugging:
1505   char *name;        // Name of lock.
1506   struct cpu *cpu;   // The cpu holding the lock.
1507   uint pcs[10];      // The call stack (an array of program
1508                      // that locked the lock.
1509 };
```

```
1573 void
1574 acquire(struct spinlock *lk)
1575 {
1576   pushcli(); // disable interrupts to avoid deadlock.
1577   if(holding(lk))
1578     panic("acquire");
1579
1580   // The xchg is atomic.
1581   while(xchg(&lk->locked, 1) != 0)
1582     ;
1583
1584   // Tell the C compiler and the processor to not move loads or stores
1585   // past this point, to ensure that the critical section's memory
1586   // references happen after the lock is acquired.
1587   __sync_synchronize();
1588
1589   // Record info about lock acquisition for debugging.
1590   lk->cpu = mycpu();
1591   getcallerpcs(&lk, lk->pcs);
1592 }
```

Disabling interrupts for kernel spinlocks (1)

- When acquiring kernel spinlock, disables interrupts on CPU core: why?
  - What if interrupt and handler requests same lock: deadlock
  - Interrupts disabled only on local core, OK to spin for lock on another core
  - Why disable interrupts before even acquiring lock? (otherwise, vulnerable window after lock acquired and before interrupts disabled)
- Disabling interrupts not needed for userspace locks like pthread mutex
  - Kernel interrupt handlers will not deadlock for userspace locks

The kernel cannot release the lock until it resumes execution, but the interrupt handler is spinning on the same lock, preventing the kernel from resuming.



Disabling interrupts for kernel spinlocks (2)

- Function pushcli: disables interrupts on CPU core before spinning for lock
  - Interrupts stay disabled until lock is released
- What if multiple spinlocks are acquired?
  - Interrupts must stay disabled until all locks are released
- Disabling/enabling interrupts:
  - pushcli disables interrupts on first lock acquire, increments count for future locks
  - popcli decrements count, renables interrupts only when all locks released

```
1662 // Pushcli/popcli are like cli/sti except that they are matched:
1663 // it takes two popcli to undo two pushcli.  Also, if interrupts
1664 // are off, then pushcli, popcli leaves them off.
1665
1666 void
1667 pushcli(void)
1668 {
1669   int eflags;
1670
1671   eflags = readeflags();
1672   cli();
1673   if(mycpu()->ncli == 0)
1674     mycpu()->intena = eflags & FL_IF;
1675   mycpu()->ncli += 1;
1676 }
1677
1678 void
1679 popcli(void)
1680 {
1681   if(readeflags()&FL_IF)
1682     panic("popcli - interruptible");
1683   if(--mycpu()->ncli < 0)
1684     panic("popcli");
1685   if(mycpu()->ncli == 0 && mycpu()->intena)
1686     sti();
1687 }
```

enable interrupts only when all locks released

cli : removes the interrupt flag
sti : sets the interrupt flag.

Recap: Context switching in xv6 (1)

- Every CPU has a scheduler thread (special process that runs scheduler code)
- Scheduler goes over list of processes and switches to one of the runnable ones
- The special function “swtch” performs the actual context switch
  - Save context on kernel stack of old process
  - Restore context from kernel stack of new process

save restore kernel context from the kernel stack.

```
2757 void
2758 scheduler(void)
2759 {
2760   struct proc *p;
2761   struct cpu *c = mycpu();
2762   c->proc = 0;
2763
2764   for(;;){
2765     // Enable interrupts on this processor.
2766     sti();
2767
2768     // Loop over process table looking for process to run.
2769     acquire(&ptable.lock);
2770     for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
2771       if(p->state != RUNNABLE)
2772         continue;
2773
2774       // Switch to chosen process.  It is the process's job
2775       // to release ptable.lock and then reacquire it
2776       // before jumping back to us.
2777       c->proc = p;
2778       switchuvm(p);
2779       p->state = RUNNING;
2780
2781       swtch(&(c->scheduler), p->context);
2782       switchkvm();
2783
2784       // Process is done running for now.
2785       // It should have changed its p->state before coming back.
2786       c->proc = 0;
2787     }
2788     release(&ptable.lock);
2789
2790   }
2791 }
```

Recap: Context switching in xv6 (2)

- After running for some time, the process switches back to the scheduler thread, when:
  - Process has terminated (exit system call)
  - Process needs to sleep (e.g., blocking read system call)
  - Process yields after running for long (timer interrupt)
- Process calls “sched” which calls “swtch” to switch to scheduler thread again
- Scheduler thread runs its loop and picks next process to run, and the story repeats

```
2662   // Jump into the scheduler, never to return.
2663   curproc->state = ZOMBIE;
2664   sched();
2665   panic("zombie exit");
2666 }
```

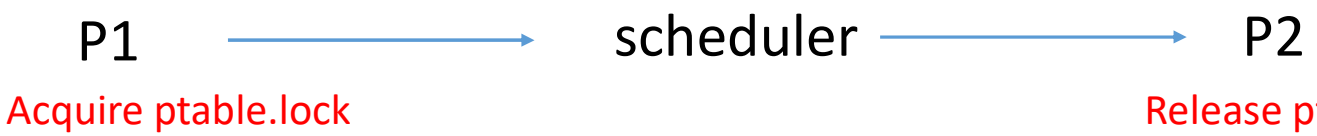
```
2894   // Go to sleep.
2895   p->chan = chan;
2896   p->state = SLEEPING;
2897
2898   sched();
2899
```

```
2826 // Give up the CPU for one scheduling round.
2827 void
2828 yield(void)
2829 {
2830   acquire(&ptable.lock);
2831   myproc()->state = RUNNABLE;
2832   sched();
2833   release(&ptable.lock);
2834 }
```

ptable.lock (1)

```
2409 struct {
2410   struct spinlock lock;
2411   struct proc proc[NPROC];
2412 } ptable;
```

- The process table protected by a lock, any access to ptable must be done with ptable.lock held
- Normally, a process in kernel mode acquires ptable.lock, changes ptable in some way, releases lock
  - Example: when allocproc allocates new struct proc
- But during context switch from process P1 to P2, ptable structure is being changed all through context switch, so when to release lock?
  - P1 acquires lock, switches to scheduler, switches to P2, P2 releases lock



ptable.lock (2)

- Every function that calls sched() to give up CPU will do so with ptable.lock held
- Which functions invoke sched() to give up CPU?
  - Yield: process gives up CPU due to timer interrupt
  - Sleep: when process wishes to block
  - Exit: when process terminates
- Every function where a process resumes after being scheduled release ptable.lock
- What functions does a process resume after swtch?
  - Yield: resuming process after yield is done
  - Sleep: resuming process that is waking up after sleep
  - Forkret: for newly created processes
- Purpose of forkret: to release ptable.lock
  - New process then returns from trap like its parent

```
2826 // Give up the CPU for one scheduling round.
2827 void
2828 yield(void)
2829 {
2830   acquire(&ptable.lock);
2831   myproc()->state = RUNNABLE;
2832   sched();
2833   release(&ptable.lock);
2834 }
```

```
2852 void
2853 forkret(void)
2854 {
2855   static int first = 1;
2856   // Still holding ptable.lock from scheduler.
2857   release(&ptable.lock);
2858
2859   if (first) {
2860     // Some initialization functions must be run i
2861     // of a regular process (e.g., they call sleep
2862     // be run from main().
2863     first = 0;
2864     iinit(ROOTDEV);
2865     initlog(ROOTDEV);
2866   }
```

That's why we return to the forkret instead of directly to the trapret so as to release the lock before going to user space.

ptable.lock (3)

P1 → scheduler → P2

Acquire ptable.lock — Release ptable.lock

- Scheduler goes into loop with lock held
- Acquire ptable.lock in P1 → scheduler picks P2 → release in P2
- Later, acquire ptable.lock in P2 → scheduler picks P3 → release in P3
- Periodically, end of looping over all processes, releases lock temporarily
  - What if no runnable process found due to interrupts being disabled? Release lock, enable interrupts, allow processes to become runnable.

    Damn smart coding practice.

```
2757 void
2758 scheduler(void)
2759 {
2760   struct proc *p;
2761   struct cpu *c = mycpu();
2762   c->proc = 0;
2763
2764   for(;;){
2765     // Enable interrupts on this processor.
2766     sti();
2767
2768     // Loop over process table looking for process to run.
2769     acquire(&ptable.lock);
2770     for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
2771       if(p->state != RUNNABLE)
2772         continue;
2773
2774       // Switch to chosen process.  It is the process's job
2775       // to release ptable.lock and then reacquire it
2776       // before jumping back to us.
2777       c->proc = p;
2778       switchuvm(p);
2779       p->state = RUNNING;
2780
2781       swtch(&(c->scheduler), p->context);
2782       switchkvm();
2783
2784       // Process is done running for now.
2785       // It should have changed its p->state before coming back.
2786       c->proc = 0;
2787     }
2788     release(&ptable.lock);
2789
2790   }
2791 }
```

It'll anyway disable the interrupt