Synchronization I

COMS W4118

References: Operating Systems Concepts, Linux Kernel Development, previous W4118s
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Single and multithreaded processes

More details on implementing threads later
Avoid race conditions

- Critical section: a segment of code that accesses a shared variable (or resource)
- No more than one thread in critical section at a time.

// ++ balance
mov 0x8049780,%eax
add $0x1,%eax
mov %eax,0x8049780
...

// -- balance
mov 0x8049780,%eax
sub $0x1,%eax
mov %eax,0x8049780
...
Critical section requirements

• Safety (aka mutual exclusion): no more than one thread in critical section at a time.

• Liveness (aka progress):
  – If multiple threads simultaneously request to enter critical section, must allow one to proceed
  – Must not depend on threads outside critical section

• Bounded waiting (aka starvation-free)
  – Must eventually allow waiting thread to proceed

• Makes no assumptions about the speed and number of CPU
  – However, assumes each thread makes progress
Critical section desirable properties

• **Efficient**: don’t consume too much resource while waiting
  – Don’t busy wait (spin wait) for a long time. Better to relinquish CPU and let other thread run

• **Fair**: don’t make one thread wait longer than others. Hard to do efficiently

• **Simple**: should be easy to use
Implementing critical section using locks

• **lock(l):** acquire lock exclusively; wait if not available

• **unlock(l):** release exclusive access to lock

```c
pthread_mutex_t  l = PTHREAD_MUTEX_INITIALIZER

void* deposit(void *arg)
{
    int i;
    for(i=0; i<1e7; ++i) {
        pthread_mutex_lock(&l);
        ++ balance;
        pthread_mutex_unlock(&l);
    }
}

void* withdraw(void *arg)
{
    int i;
    for(i=0; i<1e7; ++i) {
        pthread_mutex_lock(&l);
        -- balance;
        pthread_mutex_unlock(&l);
    }
}
```
Outline

• Critical section requirements

• Implementing locks

• Readers-writer lock
Version 1: Disable interrupts

- **Can cheat on uniprocessor**: implement locks by disabling and enabling interrupts
  
  ```c
  lock()
  {  
      disable_interrupt();  
  }
  unlock()
  {  
      enable_interrupt();  
  }
  ```

- **Good**: simple!

- **Bad**:
  - Both operations are **privileged**, can’t let user program use
  - Doesn’t work on **multiprocessors**
  - Can’t use for long critical sections
**Version 2: Software Locks**

- **Peterson’s algorithm**: software-based lock implementation (2 page paper with proof)
- **Good**: doesn’t require much from hardware
- **Only assumptions**:
  - Loads and stores are atomic
  - They execute in order
  - Does not require special hardware instructions

Software-based lock: 1st attempt

```c
// 0: lock is available, 1: lock is held by a thread
int flag = 0;

lock()
{
    while (flag == 1) ; // spin wait
    flag = 1;
}

unlock()
{
    flag = 0;
}
```

- Idea: use one flag, test then set; if unavailable, **spin-wait**
- Problem?
  - **Not safe**: both threads can be in critical section
  - **Not efficient**: busy wait, particularly bad on uniprocessor (will solve this later)
Unsafe software lock, 1\textsuperscript{st} attempt

```plaintext
lock()
{
    1: while (flag == 1) ; // spin wait
    2: flag = 1;

    flag=0;
}

Thread 0:
call lock()
1: while (flag ==1) // it is 0, so continue

2: flag = 1;

Thread 1:
call lock()
1: while(flag == 1) // it is 0, so continue

2: flag = 1; // ! Thread 0 is already in critical section
```

In general, adversarial scheduler model useful to think about concurrency problems
Software-based locks: 2\textsuperscript{nd} attempt

// 1: a thread wants to enter critical section, 0: it doesn’t
int flag[2] = {0, 0};

lock()
{
    flag[self] = 1; // I need lock
    while (flag[1- self] == 1)
    {
        // spin wait
    }
}

unlock()
{
    flag[self] = 0;
}

• Idea: use per thread flags, set then test, to achieve mutual exclusion

• Why doesn’t work?
  – Not live: can deadlock
Deadlock: 2nd attempt

// 1: a thread wants to enter critical section, 0: it doesn’t
int flag[2] = {0, 0};

lock()
{
    flag[\[self\]] = 1; // I need lock
    while (flag[\[1- self\]] == 1)
    ; // spin wait
}

unlock()
{
    // not any more
    flag[\[self\]] = 0;
}

Thread 0
call lock()
flag[0] = 1;

Thread1
flag[1] = 1;
while (flag[0] == 1);
// spins forever!
...

while (flag[1] == 1);
// spins forever too!
Software-based locks: 3\textsuperscript{rd} attempt

// whose turn is it?
int turn = 0;

lock()
{
    // wait for my turn
    while (turn == 1 - self)
    {
        // spin wait
    }
}

unlock()
{
    // I’m done. your turn
    turn = 1 - self;
}

- Idea: strict alternation to achieve mutual exclusion
- Why doesn’t work?
  - Not live: depends on threads outside critical section
  - Can’t handle repeated calls to lock by same thread
Software-based locks: final attempt (Peterson’s algorithm)

// whose turn is it?
int turn = 0;
// 1: a thread wants to enter critical section, 0: it doesn’t
int flag[2] = {0, 0};

lock()
{
    flag[self] = 1; // I need lock
    turn = 1 - self;
    // wait for my turn
    // wait for my turn
    while (flag[1-self] == 1 && turn == 1 - self)
    ; // spin wait while the
    // other thread has intent
    // AND it is the other
    // thread’s turn
}

unlock()
{
    // not any more
    flag[self] = 0;
}

• Why works?
  – Safe?
  – Live?
  – Bounded wait?
Software-based lock

• Problem
  – It’s hard!
  – N>2 threads? (Lamport’s Bakery algorithm)
  – Modern out of order processors?
Multiprocessor Challenges

• Modern processors are out-of-order/speculative
  – Reorder instructions to keep execution units full
  – Try very hard to avoid inconsistency
  – Guarantees valid only within single execution stream

• Memory access guarantees on x86
  – x86 is relatively conservative with reordering
  – Loads not reordered with other loads
  – Stores not reordered with other stores
  – Stores not reordered with older loads
  – All loads and stores to same location are not reordered
  – Load can reorder with older store to different addr

• Breaks Peterson’s algorithm!

Reference: http://www.linuxjournal.com/article/8211
Instruction Reordering affects Locking

Thread 0

Lock: flag[0] = 1; // I need lock
    turn = 1;
    while (flag[1]==1 && turn==1);
}

Thread 1

Lock: flag[1] = 1; // I need lock
    turn = 0;
    while (flag[0]==1 && turn==0);
}

• Possible for mutual exclusion to be violated?
  – Yes!

Lock: r1 = Load(flag[1])

Reorder

turn = 1;
flag[0] = 1; // I need lock
while (r1==1 && turn==1);
// flag[1]==0
}

Lock: flag[1] = 1; // I need lock
    turn = 0;
    while (flag[0]==1 && turn==0);
    // flag[0]==0
}
Memory Barriers

• A memory barrier or fence
  – Ensures that all memory operations up to the barrier are executed before proceeding

• x86 provides several memory fence instructions
  – Relatively expensive (100s of cycles)
  – mfence: all prior memory accesses completed
  – lfence: all prior loads completed
  – sfence: all prior stores flushed

```c
lock() {
    flag[self] = 1; // I need lock
    turn = 1 – self;
    sfence; // Store barrier
    while (flag[1-self] == 1 && turn == 1 – self);
}
```
Lamport’s Bakery Algorithm

• Support more than 2 processes
  – Integer tokens (increasing numbers)
  – Each customer gets next largest token
  – Same token? Smaller thread_id gets priority
  – Smallest token enters critical region

bool flag[1..NUM_THREADS] = {0}; // Want to enter
int token[1..NUM_THREADS] = {0}; // My token

lock(i) { // Lock by thread i
  flag[i] = 1;
  token[i] = 1 + max(token[0..NUM_THREADS-1]);
  flag[i] = 0;
  for (j = 1; j <= NUM_THREADS; j++) {
    while (flag[j]); // Is j getting token?
    while ((token[j] && ((token[j], j) < (token[i], i)))); // j has smaller token?
  }
}

unlock(integer i) {
  token[i] = 0;
}

Version 3: Hardware Instructions

// 0: lock is available, 1: lock is held by a thread
int flag = 0;

lock()
{
    while(test_and_set(&flag))
    {
        flag = 0;
    }
}

unlock()
{
    flag = 0;
}

• Problem with the test-then-set approach: test and set are not atomic

• Fix: special atomic operation
  – int test_and_set (int *lock) {
      int old = *lock;
      *lock = 1;
      return old;
  }
  – Atomically returns *lock and sets *lock to 1
Implementing test_and_set on x86

```c
long test_and_set(volatile long* lock)
{
    int old;
    asm("xchg %0, %1"
         : "=r"(old), "+m"(*lock) // output
         : "0"(1) // input
         : "memory" // can clobber anything in memory
    );
    return old;
}
```

- **xchg reg, addr**: atomically swaps *addr* and reg
- Spin locks on x86 are implemented using this instruction
- x86 also provides a `lock` prefix that allows bus to be locked for inst
- In Linux:
  - Arch independent: `kernel/spinlock.c`
  - Arch dependent: `arch/x86/include/asm/spinlock.h`
Spin-wait or block?

- Problem of spin-wait: waste CPU cycles
  - Worst case: thread holding a busy-wait lock gets preempted, other threads try to acquire the same lock

- On uniprocessor: should not use spin-lock
  - Yield CPU when lock not available (need OS support)

- On multi-processor
  - Thread holding lock gets preempted ➔ ???
  - Correct action depends on how long before lock release
    - Lock released “quickly” ➔ ?
    - Lock released “slowly” ➔ ?
Problem with simple yield

```c
lock()
{
    while(test_and_set(&flag))
        yield();
}
```

- **Problem:**
  - Still a lot of context switches: thundering herd
  - Starvation possible

- **Why?** **No control** over who gets the lock next
- **Need explicit control** over who gets the lock
Version 4: Sleep Locks

lock() {
    while (!test_and_set(&flag)) {
        add myself to wait queue
        yield
    }
}

unlock() {
    flag = 0
    if(any thread in wait queue) {
        wake up one wait thread
        ...
    }
}

• The idea: add thread to queue when lock unavailable; in unlock(), wake up one thread in queue

• Problem I: lost wakeup

• Problem II: wrong thread gets lock
lost wakeup

lock() {
1: while (test_and_set(&flag))
2: add myself to wait queue
3: yield
...
}

unlock() {
4: flag = 0
5: if (any thread in wait queue)
6: wake up one wait thread
...
}

Thread 0:
call lock()
while (test_and_set(&flag)) {

add myself to wait queue
yield
} // wait forever (or until next unlock)!

Thread 1

call unlock()
flag = 0
if (any thread in wait queue) // No!

wake_up_one_wait_thread
Wrong thread gets lock

lock() {
  1: while (test_and_set(&flag))
  2: add myself to wait queue
  3: yield
  ...
}

unlock() {
  4: flag = 0
  5: if (any thread in wait queue)
     6: wake up one wait thread
  ...
}

Thread 0: call lock()
call lock() while (test_set(&flag))
  add myself to wait queue
  yield

Thread 1 call unlock()
  flag = 0
  if (thread in wait queue)
    wake_up_thread

Thread 2 call lock()
  while (test_set(&flag))

• Fix: unlock() directly transfers lock to waiting thread
typedef struct __mutex_t {
    int flag;     // 0: mutex is available, 1: mutex is not available
    int guard;    // guard lock to avoid losing wakeups
    queue_t *q;   // queue of waiting threads
} mutex_t;

void lock(mutex_t *m) {
    while (test_and_set(m->guard)) //acquire guard lock by spinning
        ;
    if (m->flag == 0) {
        m->flag = 1; // acquire mutex
        m->guard = 0;
    } else {
        enqueue(m->q, self);
        m->guard = 0;
        yield();
    }
}

void unlock(mutex_t *m) {
    while (test_and_set(m->guard)) //release mutex; no one wants mutex
        ;
    if (queue_empty(m->q))
        // direct transfer mutex to next thread
        wakeup(dequeue(m->q));
    else
        m->guard = 0;
}
Adaptive Mutexes

- **Cons of Spinlocks**
  - Inefficient if lock is held for long duration
- **Cons of Sleeplocks**
  - Higher overhead, state maintenance
- **Solaris, OS X, FreeBSD**
  - Idea: use spinlock if holder is currently running, sleeplock otherwise
  - Best of both worlds
Outline

• Critical section requirements

• Implementing locks

• Readers-writer lock
Readers-Writers problem

• A reader is a thread that needs to look at the shared data but won’t change it

• A writer is a thread that modifies the shared data

• Example: making an airline reservation

• Courtois et al 1971
Readers-writer lock

```c
rwlock_t lock;

**Writer**
```write_lock (&lock);
.
// write shared data
.
write_unlock (&lock);

**Reader**
```read_lock (&lock);
.
// read shared data
.
read_unlock (&lock);

• **read_lock**: acquires lock in read (shared) mode
  – Lock is not acquired or is acquired in read mode ➔ success
  – Otherwise (lock is in write mode) ➔ wait

• **write_lock**: acquires lock in write (exclusive) mode
  – Lock is not acquired ➔ success
  – Otherwise ➔ wait
Implementing readers-writer lock

```c
struct rwlock_t {
    int nreader;       // init to 0
    lock_t guard;      // init to unlocked
    lock_t lock;       // init to unlocked
};

write_lock(rwlock_t *l)
{
    lock(&l->lock);
}

write_unlock(rwlock_t *l)
{
    unlock(&l->lock);
}

read_lock(rwlock_t *l)
{
    lock(&l->guard);
    ++ nreader;
    if(nreader == 1) // first reader
        lock(&l->lock);
    unlock(&l->guard);
}

read_unlock(rwlock_t *l)
{
    lock(&l->guard);
    -- nreader;
    if(nreader == 0) // last reader
        unlock(&l->lock);
    unlock(&l->guard);
}

Problem: may starve writer!
```
Driving out readers in a RW-Lock

```c
struct rwlock_t {
    int nreader;       // init to 0
    lock_t guard;     // init to unlocked
    lock_t lock;      // init to unlocked
    lock_t writer;    // init to unlocked
};

write_lock(rwlock_t *l)
{
    lock(&l->writer);
    lock(&l->lock);
    unlock(&l->guard);
    unlock(&l->writer);
}

read_lock(rwlock_t *l)
{
    lock(&l->writer);
    lock(&l->guard);
    ++ nreader;
    if(nreader == 1) // first reader
        lock(&l->lock);
    unlock(&l->guard);
    unlock(&l->writer);
}

write_unlock(rwlock_t *l)
{
    unlock(&l->lock);
}

read_unlock(rwlock_t *l)
{
    lock(&l->guard);
    -- nreader;
    if(nreader == 0) // last reader
        unlock(&l->lock);
    unlock(&l->guard);
}

Q: In write_lock, can we just use guard instead of writer lock?