CSE4509 Operating Systems

Locking

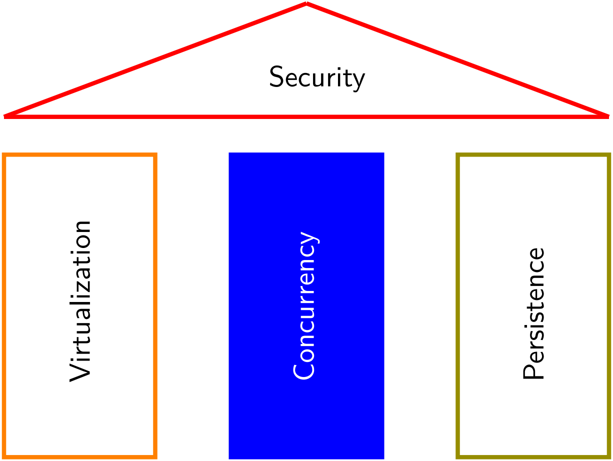
Salman Shamil

United International University (UIU)

Summer 2025

Original slides by Mathias Payer and Sanidhya Kashyap [EPFL]

Concurrency



Lecture Topics

- Abstraction: locks to protect shared data structures
- Mechanism: interrupt-based locks
- Mechanism: atomic hardware locks
- Busy waiting (spin locks) versus wait queues

This slide deck covers chapters 28, 29, 30 in OSTEP.

Race Conditions

- Concurrent execution leads to race conditions
  - Access to shared data must be mediated
- **Critical section:** part of code that accesses shared data
- **Mutual exclusion:** only one process is allowed to execute critical section at any point in time
- **Atomicity:** critical section executes as an uninterruptible block

A **mechanism** to achieve atomicity is through locking.

Locks: Basic Idea

- Lock variable protects critical section
- All threads competing for *critical section* share a lock
- Only one thread succeeds at acquiring the lock (at a time)
- Other threads must wait until lock is released

```
lock_t mutex;
...
lock(&mutex);
cnt = cnt + 1;
unlock(&mutex);
```

Locks: Basic Idea

- Requirements: mutual exclusion, fairness, and performance
  - **Mutual exclusion**: only one thread in critical section
  - **Fairness**: all threads should eventually get the lock
  - **Performance**: low overhead for acquiring/releasing lock
- Lock implementation requires hardware support
  - ... and OS support for performance

Lock Operations

- `void lock(lock_t *lck)`: acquires the lock, current thread owns the lock when function returns
- `void unlock(lock_t *lck)`: releases the lock

Lock Operations

- `void lock(lock_t *lck)`: acquires the lock, current thread owns the lock when function returns
- `void unlock(lock_t *lck)`: releases the lock

Note that we assume that the application *correctly* uses locks for *each* access to the critical section.

Interrupting Locks

- Turn off interrupts when executing critical sections
  - Neither hardware nor timer can interrupt execution
  - Prevent scheduler from switching to another thread
  - Code between interrupts executes atomically

```
void acquire(lock_t *l) {
  disable_interrupts();
}

void release(lock_t *l) {
  enable_interrupts();
}
```

Interrupting Locks (Disadvantages)

- No support for locking multiple locks
- Only works on uniprocessors (no support for locking across cores in multicore system)
- Process may keep lock for arbitrary length
- Hardware interrupts may get lost (hardware only stores information that interrupt X happened, not how many times it happened)

Interrupting Locks (Perspective)

- Interrupt-based locks are extremely simple
- Work well for low-complexity code

Interrupting Locks (Perspective)

- Interrupt-based locks are extremely simple
- Work well for low-complexity code

- Implementing locks through interrupts is great for MCUs

(Faulty) Spin Lock

- Use a shared variable to synchronize access to critical section

```c
bool lock1 = false;

void acquire(bool *lock) {
  while (*lock); /* spin until we grab the lock */
  *lock = true;
}

void release(bool *lock) {
  *lock = false
}
```

(Faulty) Spin Lock

- Use a shared variable to synchronize access to critical section

```
bool lock1 = false;

void acquire(bool *lock) {
  while (*lock); /* spin until we grab the lock */
  *lock = true;
}

void release(bool *lock) {
  *lock = false
}
```

Bug: both threads can grab the lock if thread is preempted before setting the lock but after the `while` loop completes.

Required Hardware Support

Locking requires an atomic *test-and-set* instruction.

```
int tas(int *addr, int val) {
  int old = *addr;
  *addr = val;
  return old;
}
```

Required Hardware Support

Locking requires an atomic *test-and-set* instruction.

```c
int tas(int *addr, int val) {
  int old = *addr;
  *addr = val;
  return old;
}
```

```c
int tas(int *addr, int val) {
  int old;
  asm volatile("lock; xchgl %0, %1" :
               "+m" (*addr), "=a" (old) :
               "1" (val) : "cc");
  return old;
}
```

Required Hardware Support

- Hardware support is required for (i) an instruction that updates memory location and returns old value and (ii) executes the instruction atomically.
- Directly encoding inline assembly is error prone, use intrinsics instead:

```
type __sync_lock_test_and_set(type *ptr, type val);
```

Test-and-set Spin Lock

```c
int lock1;

void acquire(int *l) {
  while (__sync_lock_test_and_set(l, 1) == 1); /* spin */
}

void release(int *l) {
  *l = 0;
}

acquire(&lock1);
critical_section();
release(&lock1);
```

Compare-and-swap Spin Lock

```
bool cas(T *ptr, T expt, T new) {
  if (*ptr == expt) {
    *ptr = new;
    return true;
  }
  return false;
}
```

The function compares the value at `*ptr` and if it is equal to `expt` then the value is overwritten with `new`. The function returns `true` if the swap happened.

```
__sync_bool_compare_and_swap(T *ptr, T expt, T new);
```

How would you implement the lock `acquire` operation?

Compare-and-swap Spin Lock

```
__sync_bool_compare_and_swap(T *ptr, T expt, T new);
```

How would you implement the lock acquire operation?

```
void acquire_cas(bool *lck) {
  while (__sync_bool_compare_and_swap(lck, false, true)
       == false);
}
```

Spin Lock: Reduce Spinning

- A simple way to reduce the cost of spinning is to `yield()` whenever lock acquisition fails
  - This is no longer a "strict" spin lock as we give up control to the scheduler every loop iteration

```
void acquire(bool *lck) {
  while (__sync_lock_test_and_set(l, 1) == 1) {
    yield();
  }
}
```

Lock Requirements: Spin Locks

- **Correctness:** mutual exclusion, progress, and, bounded
  - Mutual exclusion: $\leq$ one thread in critical section at a time
  - Progress (deadlock freedom): one waiting process will proceed
  - Bounded (no starvation): eventually each process will proceed
- Fairness: each thread waits for the same amount of time
- Performance: CPU is not used unecessarily

Lock Requirements: Spin Locks

- **Correctness:** mutual exclusion, progress, and, bounded
  - Mutual exclusion: $\leq$ one thread in critical section at a time
  - Progress (deadlock freedom): one waiting process will proceed
  - Bounded (no starvation): eventually each process will proceed
- Fairness: each thread waits for the same amount of time
- Performance: CPU is not used unecessarily

Spinlocks are unfair (threads race for lock) and hog performance (spinning and burning CPU time)!

Queue Lock

- Idea: instead of spinning, put threads on a queue
- Wake up thread(s) when lock is released
  - Wake up all threads to have them race for the lock
  - Selectively wake one thread up for fairness

Queue Lock Implementation: nptl

```
/* Bit 31 clear means unlocked; bit 31 set means locked.
   Remaining bits encode num. interested threads. */
static inline void mutex_lock(int *mutex) {
  int v;
  /* Bit 31 was clear, we got the mutex.  (fastpath). */
  if (atomic_bit_test_set(mutex, 31) == 0) return;
  atomic_increment(mutex);
  while (1) {
    if (atomic_bit_test_set(mutex, 31) == 0) {
      atomic_decrement(mutex); return;
    }
    /* We have to wait. Make sure futex is act. locked */
    v = *mutex;
    if (v >= 0) continue;
    futex_wait(mutex, v);
  }
}
```

```c
static inline void mutex_unlock(int *mutex) {
  /* Adding 0x80000000 to the counter results in 0 iff
     there are no other waiting threads (fastpath).  */
  if (atomic_add_zero(mutex, 0x80000000)) return;

  /* There are other threads waiting, wake one up. */
  futex_wake(mutex, 1);
}
```

Do you want to know more? Check out the Linux futex system call.

Comparison spinlock / queue lock

- Spinlock works well when critical section is short and rare and we execute on more than one CPU (i.e., no context switch, likely to acquire lock soon)
- Queue locks work well when critical section is longer or more frequent (i.e., high contention, likelihood that thread must wait)

Comparison spinlock / queue lock

- Spinlock works well when critical section is short and rare and we execute on more than one CPU (i.e., no context switch, likely to acquire lock soon)
- Queue locks work well when critical section is longer or more frequent (i.e., high contention, likelihood that thread must wait)
- Hybrid approach: spin for a while, then yield and enqueue

Lock principles

- Locks protect access to shared data structures
- Shared kernel data structures rely on locks
- Locking strategy: coarse-grained (one lock) versus fine-grained (many locks)
- OS only provides locks, locking strategy is up to programmer

Lock best practices

- When acquiring a lock, recheck assumptions
- Ensure that all shared information is refreshed (and not stale)
- Multiple threads may wake up and race for the lock (i.e., loop if unsuccessful)

Summary

- Locks enforce mutual exclusion for critical section (i.e., an object that can only be owned by a single thread)
- Trade-offs between spinlock and queue lock
  - Time lock is held
  - Contention for lock
  - How many concurrent cores execute
- Locking requires kernel support or atomic instructions
  - **test-and-set** atomically modifies the contents of a memory location, returning its old value
  - **compare-and-swap** atomically compares the contents of a memory location to a given value and, iff they are equal, modifies the contents of that memory location to a given new value.