



CS3281 / CS5281

Synchronization

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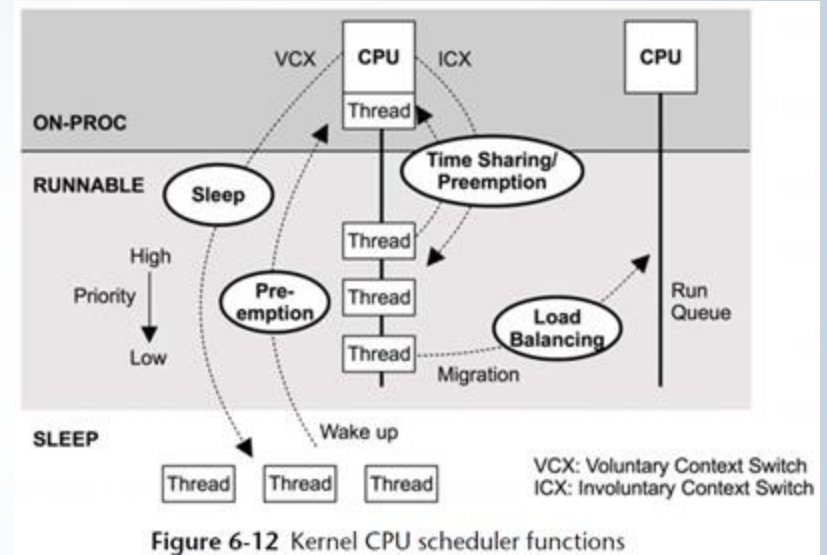


Review

- Threads enable concurrency
 - Data sharing and non-atomic operations can lead to race conditions
- Most architectures provide atomic machine instructions that provide the building blocks for synchronization primitives
- The test-and-set instruction is an example of such an instruction; it does two things atomically
 - Obtain the previous value of a variable
 - Update the current value

Thread Scheduling in More Detail

- Time sharing is driven by the timer interrupt
 - Calls `scheduler_tick()`, which invokes the scheduler to see if another thread should run
- Figure on the right shows the functions of the scheduler
 - Time sharing: every runnable thread gets a chance to run; highest priority goes first
 - Preemption: the scheduler can preempt the currently running thread and run another
 - Load balancing: the scheduler can move runnable threads to other CPUs



*Figure from *Systems Performance Enterprise and the Cloud* by Brendan Gregg

Mutexes

- Spin-locks are usually not the right solution for locking
 - They waste CPU cycles when the lock is contended
- Better solution is to *sleep* if the lock is not available
 - Have the OS wake you up when the lock is available
- Linux provides mutexes for just this purpose
 - Part of the POSIX library

pthread Mutexes

- Data type:
 - pthread_mutex_t
- Operations:
 - int pthread_mutex_lock(pthread_mutex_t *mutex);
 - int pthread_mutex_unlock(pthread_mutex_t *mutex);
- Typical use:

```
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;

void *thread_func(void *arg)
{
    pthread_mutex_lock(&mtx); // get the lock
    // access shared data
    pthread_mutex_unlock(&mtx); // release the lock
}
```

Deadlocks with Mutexes

- Consider the following scenario

Thread A	Thread B
1. <code>pthread_mutex_lock(mutex1);</code>	1. <code>pthread_mutex_lock(mutex2);</code>
2. <code>pthread_mutex_lock(mutex2);</code> blocks	2. <code>pthread_mutex_lock(mutex1);</code> blocks

- The result is a deadlock!
- Lesson: threads should always acquire locks in the same order

*Figure from *The Linux Programming Interface* by Michael Kerrisk



Locking the Same Lock

- What if the same thread tries to obtain the same mutex multiple times?
 - The result depends on how the mutex was initialized
- Types of pthread mutexes:
 - PTHREAD_MUTEX_DEFAULT or PTHREAD_MUTEX_NORMAL
 - Results in a deadlock if the same pthread tries to lock it a second time using the pthread_mutex_lock subroutine without first unlocking it. This is the default type.
 - PTHREAD_MUTEX_ERRORCHECK
 - Avoids deadlocks by returning a non-zero value if the same thread attempts to lock the same mutex more than once without first unlocking the mutex.
 - PTHREAD_MUTEX_RECURSIVE
 - Allows the same pthread to recursively lock the mutex using the pthread_mutex_lock subroutine without resulting in a deadlock or getting a non-zero return value from pthread_mutex_lock. The same pthread has to call the pthread_mutex_unlock subroutine the same number of times as it called pthread_mutex_lock subroutine in order to unlock the mutex for other pthreads to use.

Linux Implementation of Mutexes

- Locking:
 - Bit 31: indicates if lock is taken
 - 1: taken
 - 0 free
 - Remaining bits: number of waiters
 - Line 7: don't return from here until we get the lock
 - Lines 8-10: check lock is free and decrement # of waiters if so
 - Decrement because we incremented
 - Line 15: check if lock is taken
 - Line 17: futex system call
 - Put calling process on queue

```
1 void mutex_lock (int *mutex) {
2     int v;
3     /* Bit 31 was clear, we got the mutex (the fastpath) */
4     if (atomic_bit_test_set (mutex, 31) == 0)
5         return;
6     atomic_increment (mutex);
7     while (1) {
8         if (atomic_bit_test_set (mutex, 31) == 0) {
9             atomic_decrement (mutex);
10            return;
11        }
12        /* We have to waitFirst make sure the futex value
13         we are monitoring is truly negative (locked). */
14        v = *mutex;
15        if (v >= 0)
16            continue;
17        futex_wait (mutex, v);
18    }
19 }
20
21 void mutex_unlock (int *mutex) {
22     /* Adding 0x80000000 to counter results in 0 if and
23     only if there are not other interested threads */
24     if (atomic_add_zero (mutex, 0x80000000))
25         return;
26
27     /* There are other threads waiting for this mutex,
28     wake one of them up. */
29     futex_wake (mutex);
30 }
```

*Figure from *Operating Systems: Three Easy Pieces* by Arpaci-Dusseau and Arpaci-Dusseau

Linux Implementation of Mutexes

- Unlocking:
 - Lines 24-25: if `*mutex == 0` after adding `0x80000000`, then nobody was waiting
 - Line 29: invoke the futex system call
 - Argument of `FUTEX_WAKE`
- `futex()` is a multiplexed system call
 - Different arguments change the behavior
 - `FUTEX_WAIT`: go to sleep until mutex is available
 - `FUTEX_WAKE`: wake up someone waiting on this mutex
- Described in paper “Futexes are Tricky” by Ulrich Drepper

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Producer-Consumer Problem

- Canonical example for condition variables: the producer-consumer problem
 - *Producer* threads produce elements
 - *Consumer* threads consume the elements produced by the producer threads
- A lock alone isn't a good solution:
 - It only ensures mutual exclusion
 - Consider the case where a consumer wants to run but there are no elements available:
 - Obtain lock
 - Check for elements
 - Release lock
 - Sleep
- Condition variables to the rescue!

Condition Variables

- A condition variable allows one thread to inform other threads about changes in the state of a shared variable (or other shared resource) and allows the other threads to wait (block) for such notification.
- Typical use:

```
pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cond_full = PTHREAD_COND_INITIALIZER;
pthread_cond_t cond_empty = PTHREAD_COND_INITIALIZER;

void *producer_func(void *arg)
{
    pthread_mutex_lock(&mtx);
    while (num_avail >= MAX_SIZE)
        pthread_cond_wait(&cond_empty, &mtx);
    num_avail++;
    pthread_cond_signal(&cond_full);
    pthread_mutex_unlock(&mtx);
}
```

Condition Variables (cont.)

- The mutex associated with a condition variable is for mutual exclusion
- The condition variable is for signaling
- Important: always check the condition in a while loop! From the previous slide

```
void *consumer_func(void *arg)
{
    pthread_mutex_lock(&mtx);
    while (num_avail <= 0)
        pthread_cond_wait(&cond_full, &mtx);
    // consumer data and process
    num_avail--;
    pthread_cond_signal(&cond_empty);
    pthread_mutex_unlock(&mtx);
}
```

This atomically:

1. Unlocks the mutex
2. Waits on the condition variable

When execution reaches here, you have obtained the mutex, so you must unlock it

Condition Variable Operations

- Basic operations: signaling and waiting
 - Signaling wakes up only one waiter
- Functions return 0 on success, non-zero on error

```
int pthread_cond_signal(pthread_cond_t *cond);  
int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
```

In-Class Exercise

- Use semaphores in the producer/consumer code in the repo



Semaphores

- Semaphores are another synchronization primitive that can be used for both signaling and mutual exclusion
 - Originally proposed by Dijkstra
- In real life: semaphore is a system of signals for communicating visually
 - Usually with flags or lights
- Conceptually: a data type with integer value and two operations:
 - P(): decrement value of integer; block if it would go below 0
 - V(): increment the value of the integer; wake a waiting thread (if any)

P for “prolaag”, a contraction of “probeer” (Dutch for “try”) and “verlaag” (“decrease”);
V for the Dutch word “verhoog” which means “increase”



Semaphores

- Like an integer with three differences:
 - When you create it, you can initialize its value to any integer
 - Afterwards you can only increase by one and decrease by one
 - When a thread decrements the semaphore, if the result is negative, the thread is blocked and cannot continue until another thread increments the semaphore
 - When a thread increments the semaphore, if other threads are waiting, one waiting thread gets unblocked
- This implies:
 - There's no way to know if a thread will block before it decrements a semaphore
 - After a thread increments a semaphore, you don't know whether it or waiting thread that woke up will continue running
 - When you increment a semaphore, you don't know whether there is any waiting thread

Semaphores

- Values:
 - Positive: number of threads that can decrement without blocking
 - Negative: number of threads that are blocked and waiting
 - Zero: No thread waiting, but trying to decrement will block
- A mutex can be implemented as a binary semaphore
 - Initialize the semaphore to 1
- “Counting” problems can initialize the semaphore to an arbitrary value
- Linux implementation: can be used across processes
 - Mutexes and condition variables only usable between threads of same process
- Data type: `sem_t` and associated functions
 - Similar to POSIX mutexes and condition variables

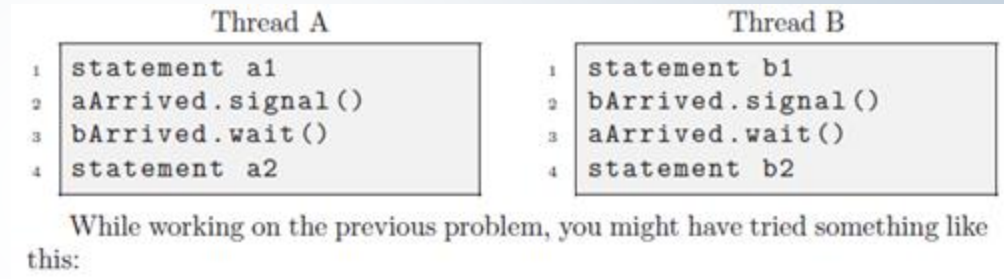
Rendezvous

- Common synchronization pattern
- Two threads (A and B)
 - A has to wait for B
 - B has to wait for A
- In other words:
 - a1 happens before b2
 - b1 happens before a2



Rendezvous Solution

- Common synchronization pattern
- Two threads (A and B)
 - A has to wait for B
 - B has to wait for A
- In other words:
 - a1 happens before b2
 - b1 happens before a2
- Solution on the right
 - Tell the other thread you've arrived
 - Then wait on the other thread



Barriers

- Another common synchronization pattern
 - “Generalizes” the Rendezvous to arbitrary number of threads
- In other words, no thread reaches the critical point until everyone has executed the rendezvous

Barrier code

```
1 rendezvous  
2 critical point
```

Synchronization Implementation

- How are all of these synchronization primitives implemented?
- If no sleeping involved: with atomic machine instructions
 - Example: spin-locks use the atomic compare and exchange instruction
- If sleeping involved: with the *futex* system call
- With pthreads, the mutex, condition variable, and semaphore operations are all defined in the C library
 - “Fast” path (i.e., the lock is free): no need to transition to kernel-space (i.e., no system call)
 - “Slow” path (i.e., lock is contended): the C library invokes the futex system call

Synchronization Implementation (cont.)

- How is the futex system call implemented?
 - Quickly check again if the resource is free
 - If not, the kernel puts the calling process on a queue associated with the lock/semaphore/condition variable
 - The kernel then switches to another process
 - Putting the process on the queue and switching to another needs to happen atomically so a wake-up isn't missed;
 - Corner cases often complicate the implementation
- When another thread/process releases the lock:
 - Check if there's anyone on the queue associated with that lock
 - If so, wake them up