Locks and semaphores

Johan Montelius

KTH

2017
Recap, what's the problem:

```
#include <pthread.h>

volatile int count = 0;

void *hello(void *arg) {
  for(int i = 0; i < 10; i++) {
    count++;
  }
}

int main() {
  pthread_t p1, p2;

  pthread_create(&p1, NULL, hello, NULL);
  pthread_create(&p2, NULL, hello, NULL);
```
Peterson’s algorithm

```c
int request[2] = {0, 0};
int turn = 0;

int lock(int id) {
    request[id] = 1;
    int other = 1-id;
    while(request[other] == 1 && turn == other) {}; // spin
    return 1;
}

void release(int id) {
    request[id] = 0;
}
```
Total Store Order

\[ \text{read b} \quad \text{read a} \]

\[ a = 1 \quad b = 1 \]

Diagram showing the sequence of operations for P1 and P2.
atomic memory operations

All CPU:s provide several versions of atomic operations that both read and write to a memory element in one atomic operation.

- **test-and-set**: swap i.e. read and write to a memory location, the simplest primitive
- **fetch-and-add/and/xor/...**: update the value with a given operation, more flexible
- **compare-and-swap**: if the memory location contains a specific value then swap
try to lock by swap

```c
int try(int *lock) {
    __sync_val_compare_and_swap(lock, 0, 1);
}
```

```assembly
    pushq   %rbp
    movq    %rsp, %rbp
    movq    %rdi, -8(%rbp)
    movq    -8(%rbp), %rdx
    movl    $0, %eax
    movl    $1, %ecx
    lock    cmpxchgl %ecx, (%rdx)
    nop
    popq    %rbp
    ret
```

*This is using GCC extensions to C, similar extensions available in all compilers.*
```c
int lock(int *lock) {
    while(try(lock) != 0) {}  
    return 1;
}

void release(int *lock) {
    *lock = 0;
}
```
int global = 0;

int count = 0;

void *hello(void *name) {
    for(int i = 0; i < 10; i++) {
        lock(&global);
        count++;
        count++;
        release(&global);
    }
}
spin locks
We need to talk to the operating system.

```c
void lock(int *lock) {
    while (try(lock) != 0) {
        sched_yield(); // in Linux
    }
}
```
For how long should we sleep?

We would like to be woken up as the lock is released - before you go-go.
void lock(lock_t *m) {
    while(try(m->guard) != 0) {};
    if(m->flag == 0) {
        m->flag = 1;
        m->guard = 0;
    } else {
        queue_add(m->queue, gettid());
        m->guard = 0;
        park();
    }
}

void unlock(lock_t *m) {
    while(try(m->guard) != 0) {};
    if(empty(m->queue)) {
        m->flag = 0;
    } else {
        unpark(dequeue(m->queue));
    }
    m->guard = 0;
}
It's not easy to get it right.

```c
/* m->flag == 1 */
:
queue_add(m->queue, gettid());
m->guard = 0;
park();
// when I wake up the flag is set
if(empty(m->queue)) {
/* m->flag == 1 */
:
queue_add(m->queue, gettid()); // don’t reset the flag
setpark();
unpark(dequeue(m->queue));
// if someone unparks now my park() is a noop
m->guard = 0;
park();
```
Introducing futex: fast user space mutex.

- `futex_wait(mutex, val)`: suspend on the mutex if its equal to `val`.
- `futex_wake(mutex)`: wake one of the threads suspended on the mutex.

*In GCC you have to call them using a syscall()*
a futex lock

```c
void lock(volatile int *lock) {
    while(try(lock) != 0) {
        *lock = 0;
        // time to sleep ...
        futex_wake(lock);
        futex_wait(lock, 1);
    }
}

void unlock(volatile int *lock) {
    *lock = 0;
    futex_wake(lock);
}
```

Not very efficient - we want to avoid calling `futex_wait()` if no one is waiting.
Using Linux futex or Sun park/unpark directly is error prone and not very portable.

It’s better to use the pthread library API, probably more efficient and definitely less problems.

Introducing pthread mutex locks:

- `pthread_mutex_t`: structure that is the mutex
- `pthread_mutex_init(pthread_mutex_t *mutex, ... *attr)`
- `pthread_mutex_destroy(pthread_mutex_t *mutex)`
- `pthread_mutex_lock(pthread_mutex_t *mutex)`
- `pthread_mutex_unlock(pthread_mutex_t *mutex)`

The lock procedure is platform specific, normally implemented as a combination of spinning and yield.
What could go wrong?

- Deadlock: the execution is stuck, no thread is making progress.
- Livelock: we’re moving around in circles, all threads think that they are doing progress but we’re stuck in a loop.
- Starvation: we’re making progress but some threads are stuck waiting.
- Unfairness: we’re making progress but some threads are given more of the resources.
Assume we have a fixed priority scheduler, three processes with high (H), medium (M) and low (L) priority and one critical resource.

- **H:** takes lock, suspends on lock
- **M:**
- **L:** takes lock
Mars Pathfinder and Priority Inversion
Some examples

- concurrent counter
- a list
- a queue
- a hash table
struct counter_t {
  int val;
}

void incr(struct counter_t *c) {
  c->val++;
}

struct counter_t {
  int val;
  pthread_mutex_t lock;
}

void incr(struct counter_t *c) {
  pthread_lock(c->lock);
  c->val++;
  pthread_unlock(c->lock);
}
Doing the right thing often has a price.
Sloppy vs Speed - do the right thing.
how about a list

*Simple solution:* protect the list with one lock.

*Concurrent solution:* allow several thread to operate on the list concurrently.

  - concurrent reading: not a problem
  - concurrent updating: .... hmm, how would you solve it?

*Can we prove that we will never end up in a dead-lock?*

*The concurrent solution might not be faster... but it's so much more challenging :-)*
What about a queue

*Simple solution:* protect the queue with one lock.

*Concurrent solution:* allow threads to add elements to the queue at the same time as other remove elements.
Simple solution: protect the table with one lock.

Concurrent solution: allow threads to add elements to the table at the same time as other remove or search for elements.
Traditionally operating systems were single threaded - the obvious solution.

The first systems that operated on multi-cpu architectures used one big kernel lock to avoid any problems with concurrency.

An operating system that is targeting multi-core architectures will today be multi threaded and use fine grain locking to increase performance.

How are things done in for example the JVM or Erlang?
The locks that we have seen are all right:

- We can take a lock and prevent others from obtaining the lock.
- If someone holds the lock we will suspend execution.
- When the lock is released we will wake up and try to grab the lock again.

We would like to suspend and only be woken up if a specified condition holds true.
What do we do now?
Introducing pthread conditional variables:

- pthread_cond_t: the data structure of a conditional variable
- pthread_cond_init(pthread_cond_t *restrict cond, ...)
- pthread_cond_destroy(pthread_cond_t *cond)
- pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex)
- pthread_cond_signal(pthread_cond_t *cond)
- pthread_cond_broadcast(pthread_cond_t *cond)

*The exact declarations are slightly more complicated, check the man pages.*
A single element buffer, multiple consumers, multiple producers.

```c
int buffer;
int count = 0;

void put(int value) {
    assert(count == 0);
    count = 1;
    buffer = value;
}

int get() {
    assert(count == 1);
    count = 0;
    return buffer;
}
```

*Let’s try to make this work.*
void produce(int val) {
    put(val);
}

int consume() {
    int val = get();
    return val;
}
add a mutex and cond variable

```c
pthread_cond_t cond;
pthread_mutex_t mutex;

produce(int val) {
    pthread_mutex_lock(&mutex);
    if (count == 1)
        pthread_cond_wait(&cond, &mutex);
    put(i);
    pthread_cond_signal(&cond);
pthread_mutex_unlock(&mutex);
}

int consume() {
    pthread_mutex_lock(&mutex);
    if (count == 0)
        pthread_cond_wait(&cond, &mutex);
    int val = get();
    pthread_cond_signal(&cond);
pthread_mutex_unlock(&mutex);
    return val;
}
```

*When does this work, when does it not work?*
If you’re signaled to wake up - it might take some time before you do wake up.
better

```c
pthread_cond_t filled, empty;
pthread_mutex_t mutex;

produce(int val) {
    pthread_mutex_lock(&mutex);
    while (count == 1)
        pthread_cond_wait(&empty, &mutex);
    :
    pthread_cond_signal(&filled);
    :
}

int consume() {
    pthread_mutex_lock(&mutex);
    while (count == 0)
        pthread_cond_wait(&filled, &mutex);
    :
    pthread_cond_signal(&empty);
    :
}
```
int buffer[MAX];
int *getp = 0;
int *putp = 0;
int count = 0;

void put(int value) {
    assert(count < MAX);
    buffer[putp] = value;
    putp = putp + 1 % MAX;
    count++;
}

int get() {
    assert(count > 0);
    int val = buffer[getp];
    getp = getp + 1 % MAX
    count--
    return val;
}
produce(int val) {
    :
    while(count == MAX)
        pthread_cond_wait(&empty, &mutex);
    :
}

int consume() {
    :
    while(count == 0)
        pthread_cond_wait(&filled, &mutex);
    :
}

Can we allow a producer to add an entry while another removes an entry?
Where are we now?

- atomic test and set: we need it
- spin locks: simple to use but have some problems
- wait and wake: avoid spinning
- condition variables: don’t wake up if it’s not time to continue

Is there more?
Semaphores

Properties of a semaphore:
- holds a number
- only allow threads to pass if number is above 0
- passing threads decrement the number
- a thread can increment the number

A semaphore is a counter of resources.
#include <semaphore.h>

sem_t: the semaphore data structure

sem_init(sem_t *sem, int pshared, unsigned int value): could be shared between processes

int sem_destroy(sem_t *sem)

sem_wait(sem_t *sem)

sem_post(sem_t *sem)