Locks and semaphores

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recap, what’s the problem

```c
#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);
    
    return 0;
}
```
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

P1

a0

P2

0b
$a = 1$
Total Store Order

\[ a = 1 \]

\[ b = 1 \]
Total Store Order

P1

a = 1

read b

P2

0

read a

b = 1

1

1

4 / 41
Total Store Order

P1

a = 1

read b

0

1

P2

a

0

read a

0

b

b = 1

1

0
atomic memory operations

All CPUs 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.
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- **compare-and-swap**: if the memory location contains a specific value then swap
int try(int *lock) {
    __sync_val_compare_and_swap(lock, 0, 1);
}

This is using GCC extensions to C, similar extensions available in all compilers.
try to lock by swap

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

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
```

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try to lock by swap

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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.
int lock(int *lock) {
    while(try(lock) != 0) {} 
    return 1; 
}
a spin-lock

```c
int lock(int *lock) {
    while(try(lock) != 0) {} 
    return 1; 
}

void release(int *lock) {
    *lock = 0; 
}
```
finally - we’re in control

```c
int global = 0;

int count = 0;

void *hello(void *name) {
    for(int i = 0; i < 10; i++) {
        lock(&global);
        count++;
        release(&global);
    }
}
```
We need to talk to the operating system.
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```c
void lock(int *lock) {
    while(try(lock) != 0) {
        sched_yield(); // in Linux
    }
}
```
For how long should we sleep?
For how long should we sleep?
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 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 = 0;
} else {
    // don't reset the flag
    unpark(dequeue(m->queue));
}
```
It's not easy to get it right.

/* m->flag == 1 */

queue_add(m->queue, gettid());
setpark();
// if someone unparks now my park() is a noop
m->guard = 0;
park();

if(empty(m->queue)) {
    m->flag = 0;
} else {
    // don't reset the flag
    unpark(dequeue(m->queue));
}

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

void lock(volatile int *lock) {
    while(try(lock) != 0) {
        // time to sleep ...
        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.
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void lock(volatile int *lock) {
    while(try(lock) != 0) {
        // time to sleep ... 
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    *lock = 0;
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Using Linux futex or Sun park/unpark directly is error prone and not very portable.

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.
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What could go wrong?

- Nothing works, will not even compile.
- 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.
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H: 

M: 

L: 

Diagram: 

0 10 20 30 40 50 60 70 80 90 100 110 120
Assume we have a fixed priority scheduler, three processes with high (H), medium (M) and low (L) priority and one critical resource.

H: 

M: 

L: 

0  10  20  30  40  50  60  70  80  90  100  110  120
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H: takes lock

M: suspends on lock

L: takes lock
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 and suspends on lock.
- **M:** Suspends on lock.
- **L:** Takes lock.

The timeline shows the execution of these processes with respect to time.
Mars Pathfinder and Priority Inversion
Some examples

- concurrent counter
- a list
- a queue
- a hash table
the concurrent counter

```c
struct counter_t {
    int val;
};

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

the concurrent counter

```c
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);
}
```
Do the right thing

*Doing the right thing often has a price.*
Doing the right thing often has a price.
sloppy counter

thread 1
sloppy counter

counter

thread 1

thread 2

Sloppy vs Speed - do the right thing.
Sloppy vs Speed - do the right thing.
sloppy counter

counter

local

thread 1

thread 2

thread 3

Sloppy vs Speed - do the right thing.
sloppy counter

0

local

thread 1

local

thread 2

local

thread 3

Sloppy vs Speed - do the right thing.
sloppy counter

counter

0

local

thread 1

1

local

thread 2

local

thread 3

local

Sloppy vs Speed - do the right thing.
sloppy counter

---

counter

0

---

thread 1

local

1

---

thread 2

local

1

---

thread 3

local

---

Sloppy vs Speed - do the right thing.
sloppy counter

counter

thread 1

2
local

thread 2

1
local

thread 3

local

Sloppy vs Speed - do the right thing.
sloppy counter

counter

2 local

thread 1

1 local

thread 2

1 local

thread 3
Sloppy vs Speed - do the right thing.
Sloppy vs Speed - do the right thing.
sloppy counter

counter

thread 1

thread 2

thread 3

local

local

local

1

2

4
sloppy counter

thread 1

thread 2

thread 3

local

counter

local

local
sloppy counter

Sloppy vs Speed - do the right thing.
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Simple solution: protect the list with one lock.
how about a list

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

**Concurrent solution:** *allow several thread to operate on the list concurrently.*
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- concurrent reading: not a problem
how about a list

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- concurrent reading: not a problem
- concurrent updating: ....
how about a list

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

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*The concurrent solution might not be faster...*
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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.
What about a queue

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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.
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An operating system that is targeting multi-core architectures will today be multi threaded and use fine grain locking to increase performance.
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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.
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- If someone holds the lock we will suspend execution.
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- 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.
the queue revisited

What do we do now?
What do we do now?
What do we do now?
What do we do now?
the queue revisited

What do we do now?

front → dummy → end
What do we do now?
the queue revisited

What do we do now?
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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.
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*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.
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}
```

*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);
}

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?
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);
}

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;
}
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}
```

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;
```
```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);
}

consume() {
    pthread_mutex_lock(&mutex);
    while (count == 0)
        pthread_cond_wait(&filled, &mutex);
    pthread_cond_signal(&empty);
}
```
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;
in *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);
    : 
}

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

```c
produce(int val) {
    : 
    while (count == MAX)
        pthread_cond_wait(&empty, &mutex);
    : 
}

int consume() { 
    : 
    while (count == 0)
        pthread_cond_wait(&filled, &mutex);
    : 
}
```
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?
atomic test and set: we need it
Where are we now?

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

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#include <semaphore.h>
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typedef struct { ... } sem_t;

sem_t: the semaphore data structure
#include <semaphore.h>

sem_t: the semaphore data structure

sem_init(sem_t *sem, int pshared, unsigned int value): could be shared between processes
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- **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)**
#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)`
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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)
#include <semaphore.h>

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`int sem_destroy(sem_t *sem)`

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`sem_post(sem_t *sem)`