Locks and semaphores

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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

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

int lock(int id) {
    request[id] = 1;
    int other = 1-id;
    turn = other;

    while(request[other] == 1 && turn == other) {}; // spin

    return 1;
}

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

P1

\[ a_0 \]

P2

\[ b_0 \]
Total Store Order

P1

\[ a = 1 \]

\[ \text{read } b \]

\[ 1 \]

P2

\[ 0 \]

\[ \text{read } a \]

\[ a \]

\[ 0 \]

\[ b = 1 \]

\[ 1 \]
Total Store Order

P1

\[ a = 1 \]

\[ a = 0 \]

\text{read } b

\text{read } a

P2

\[ b = 1 \]

\[ b = 0 \]

1

0

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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
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int try(int *lock) {
    return __sync_val_compare_and_swap(lock, 0, 1);
}
try to lock by swap

```c
int try(int *lock) {
    return __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.
try to lock by swap

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int try(int *lock) {
    return __sync_val_compare_and_swap(lock, 0, 1);
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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;
}
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);
    }
}
```
spin locks
spin locks
avoid spinning

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 unlock(lock_t *m) {

    while(try(m->guard) != 0) {};

    if(empty(m->queue)) {
        m->flag = 0;
    } else {
        unpark(dequeue(m->queue));
    }
    m->guard = 0;
}
void lock(lock_t *m) {
    while(try(m->guard) != 0) {{};
    if(m->flag == 0) {
        m->flag = 1;
        m->guard = 0;
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        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.

```c
/* 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));
}
```
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()*
void lock(volatile int *lock) {
    while(try(lock) != 0) {
        // time to sleep ...
        futex_wait(lock, 1);
    }
}
```c
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);
}
```
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.
Using Linux futex or Sun park/unpark directly is error prone and not very portable.
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The lock procedure is platform specific, normally implemented as a combination of spinning and yield.
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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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: 
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:
Resources, priorities and scheduling

Assume we have a fixed priority scheduler, three processes with high (H), medium (M) and low (L) priority and one critical resource.

H: ![High Priority Process]
M: ![Medium Priority Process]
L: ![Low Priority Process]
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H: [Red bars]
M: [Blue bar]
L: [Green bars]

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: \[\text{H takes lock}\]

M: \[\text{M takes lock}\]

L: \[\text{L takes lock}\]
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

M: takes 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 suspends on lock

M: 

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.
Mars Pathfinder and Priority Inversion
Some examples

- concurrent counter
- a list
- a queue
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++;
}
```

```c
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.
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 counter

counter

thread 1

thread 2

thread 3

Sloppy vs Speed - do the right thing.
sloppy counter

counter

local

thread 1

local

thread 2

local

thread 3

Sloppy vs Speed - do the right thing.
sloppy counter

counter

1

local

thread 1

0

local

thread 2

local

thread 3

Sloppy vs Speed - do the right thing.
sloppy counter

thread 1

thread 2

thread 3

local

local

local

Sloppy vs Speed - do the right thing.
sloppy counter

counter

thread 1

thread 2

thread 3

local

local

local

Sloppy vs Speed - do the right thing.
sloppy counter

counter

thread 1

local

2

thread 2

local

1

thread 3

local

1

Sloppy vs Speed - do the right thing.
sloppy counter

counter

local

thread 1

local

thread 2

local

thread 3

Sloppy vs Speed - do the right thing.
sloppy counter

counter

3 local

downthread 1

2 local
downthread 2

1 local
downthread 3

Sloppy vs Speed - do the right thing.
sloppy counter

counter

thread 1

4 local

do thread 1

thread 2

2 local

do thread 2

thread 3

1 local

do thread 3

Sloppy vs Speed - do the right thing.
sloppy counter

counter

4 local
thread 1

2 local
thread 2

2 local
thread 3

Sloppy vs Speed - do the right thing.
sloppy counter

counter

thread 1

5 local

thread 2

2 local

thread 3

2 local
sloppy counter

counter

5

local

5

local

2

local

2

thread 1

thread 2

thread 3

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

thread 1

thread 2

thread 3

local

local

local

thread 1

thread 2

thread 3

counter

5
Sloppy vs Speed - do the right thing.
how about a list

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

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

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- concurrent reading: not a problem
Simple solution: protect the list with one lock.

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- concurrent reading: not a problem
- concurrent updating: ....
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?
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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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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- When the lock is released we will wake up and try to grab the lock again.
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- If someone holds the lock we will suspend execution.
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We would like to suspend and only be woken up if a specified condition holds true.
What do we do now?
What do we do now?
What do we do now?
What do we do now?
conditional variables

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.
A single element buffer, multiple consumers, multiple producers.

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    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;
```
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(val);
    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?
add a mutex and cond variable

```c
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pthread_mutex_t mutex;

produce(int val) {
    pthread_mutex_lock(&mutex);
    if (count == 1)
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        pthread_cond_wait(&cond, &mutex);
    int val = get();
    pthread_cond_signal(&cond);
    pthread_mutex_unlock(&mutex);
    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(val);
    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?
a race condition

If you’re signaled to wake up - it might take some time before you do wake up.
```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); 
    : 
}
final touch

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
atomic test and set: we need it
spin locks: simple to use but have some problems
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
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
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.
Properties of a semaphore:

- A semaphore is a counter of resources.
- Semaphores hold a number.
- Threads are only allowed to pass if the number is above 0.
- Threads can decrement the number on passing.
- A thread can increment the number.

Properties of a semaphore:
  - holds a number
Properties of a semaphore:
- holds a number
- only allow threads to pass if the number is above 0
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Semaphores

A semaphore is a counter of resources.

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
#include <semaphore.h>
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`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
#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)
#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)
POSIX semaphores

- `#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)`
#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)
HAPPY-GO-LUCKY

Summary

“Vastly entertaining and very funny”

“Fresh and funny, joyful and life-affirming”

“A joy to behold”

“A delight”

Winner

Best Actress

Emma Stone
Summary