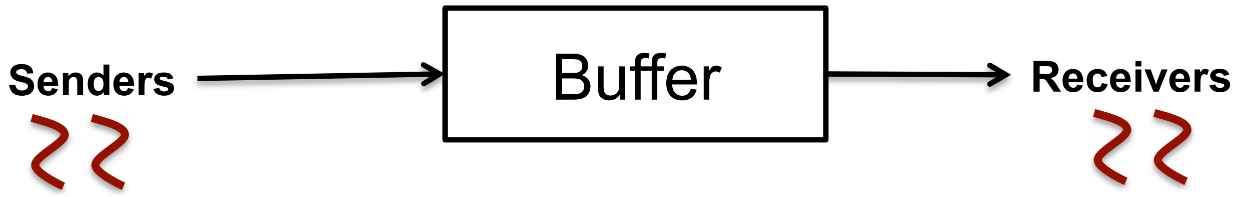
Condition Variable

Jinyang Li

based on slides by Tiger Wang

Example I



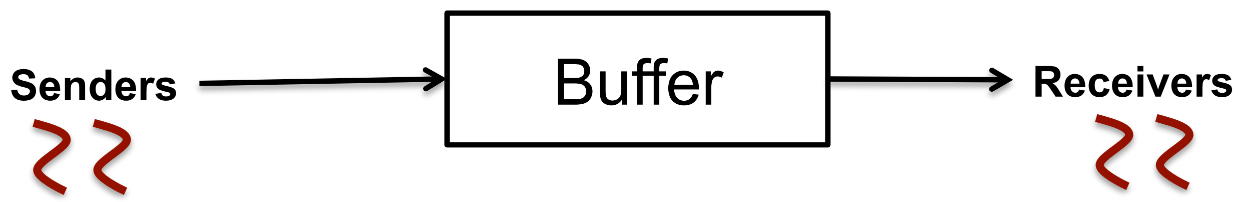
```
typedef struct {
  int data[MAX];
  int size;
} buffer_t;

buffer_t buf;
int result;
```

```
void* sender(void *arg){

  srandom(time());

  while(1) {
    if (buf.size < MAX) {
      buf.size++;
      buf.data[buf.size - 1] = random();
    }
  }
    return NULL;
}
```

```
void* receiver(void *arg){

  srandom(time());

  while(1) {
    if (buf.size > 0) {
      total += buf.data[buf.size - 1];
      buf.size--;
    }
  }
    return NULL;
}
```

Example I

```
typedef struct {
  int data[MAX];
  int size;
  pthread_mutex_t mutex;
} buffer_t;

buffer_t buf;
int result;
```



```
void* sender(void *arg){

  srandom(time());

  while(1) {
    pthread_mutex_lock(&buf.mutex);
    if (buf.size < Max) {
      buf.size = buf.size + 1;
      buf.data[buf.size - 1] = random();
    }
    pthread_mutex_unlock(&buf.mutex);
  }
    return NULL;
}
```

```
void* receiver(void *arg){

  srandom(time());

  while(1) {
    pthread_mutex_lock(&buf.mutex);
    if (buf.size > 0) {
      total += buf.data[buf.size - 1];
      buf.size = buf.size - 1;
    }
    pthread_mutex_unlock(&buf.mutex);
  }
    return NULL;
}
```

Problem?

Problem

- Thread needs to be informed on some condition
  - e.g. buffer is non-empty or non-full
- Naive solution: busy checking whether condition is true or false
  - X wastes CPU

✓ Solution: a notification mechanism

Condition variables

- A mechanism to block a thread until some condition becomes true

- Conditional variable API:
  - `pthread_cond_t`
  - `pthread_cond_wait / pthread_cond_timedwait`
  - `pthread_cond_signal`
  - `pthread_cond_broadcast`

pthread_cond_wait

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

- Atomically releases `mutex` and causes the calling thread to be put on an internal waiting queue for `cond`.

- On successful return, `mutex` is locked (which the calling thread should unlock later)

No other thread can grab the released mutex before the calling thread is put in the waiting queue

pthread_cond_signal

```
int pthread_cond_signal(pthread_cond_t *cond);
```

- Unblock at least one of the threads blocked on `cond`

```
int pthread_cond_broadcast(pthread_cond_t *cond);
```

- Unblock all threads blocked on a condition variable.

Pseudo-code

Thread 1

```
pthread_cond_wait(cond,  mutex)
```

atomic

1. unlock `mutex`
2. block on `cond`

Pseudo-code

Thread 1

```
pthread_cond_wait(cond,  mutex)
```

atomic

1. unlock mutex
2. block on cond

Thread 2

```
pthread_cond_signal(cond)
```

1. Wake up a thread blocked on cond

Pseudo-code

Thread 1

```
pthread_cond_wait(cond, mutex)
```

atomic: suspend

1. unlock mutex
2. block on cond

Thread 2

```
pthread_cond_signal(cond)
```

1. Wake up a thread blocked on cond

Thread 1

```
pthread_cond_wait(cond, mutex)
```

atomic: wakeup

1. lock mutex
2. return 0

Example II – hello bye

```
pthread_mutex_t mutex;
bool saidHello = false;
```

```
void* sayHello(void *arg){

  pthread_mutex_lock(&mutex);
  printf(“hello ”);
  saidHello = true;
  pthread_mutex_unlock(&mutex);
  return NULL;
}
```

```
void* sayBye(void *arg){

  pthread_mutex_lock(&mutex);
  if (saidHello) {
     printf(“bye\n”);
  }
  pthread_mutex_unlock(&mutex);
  return NULL;
}
```

Example II – hello bye

```
pthread_mutex_t mutex;
pthread_cond_t cond;
bool saidHello = false;
```

```
void* sayHello(void *arg){

   pthread_mutex_lock(&mutex);
   printf("hello ");
   saidHello = true;
   pthread_cond_signal(&cond);
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

```
void* sayBye(void *arg){

   pthread_mutex_lock(&mutex);
   while(!saidHello) {
      pthread_cond_wait(&mutex, &cond);
   }
   printf("bye\n");
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

Example II – hello bye

```
pthread_mutex_t mutex;
pthread_cond_t cond;
bool saidHello = false;
```

```
void* sayHello(void *arg){

   pthread_mutex_lock(&mutex);
   printf(“hello ”);
   saidHello = true;
   pthread_cond_signal(&cond);
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

```
void* sayBye(void *arg){

   pthread_mutex_lock(&mutex);
   while(!saidHello) {
      pthread_cond_wait(&mutex, &cond);
   }
   printf(“bye\n”);
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

Use “while” instead of “if”,
because spurious wakeups from the
`pthread_cond_timedwait()` or
`pthread_cond_wait()` functions may occur.

Example II – hello bye

```
pthread_mutex_t mutex;
pthread_cond_t cond;
bool saidHello = false;
```

```
void* sayHello(void *arg){

  ~~pthread_mutex_lock(&mutex);~~
  printf("hello ");
  saidHello = true;
  pthread_cond_signal(&cond);
  ~~pthread_mutex_unlock(&mutex~~);
  return NULL;
}
```

```
void* sayBye(void *arg){

   pthread_mutex_lock(&mutex);
   while(!saidHello) {
      pthread_cond_wait(&mutex, &cond);
   }
   printf("bye\n");
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

Why grab a lock to protect signal?
Is this a must?

Example II – hello bye

```
pthread_mutex_t mutex;
pthread_cond_t cond;
bool saidHello = false;
```

```
void* sayHello(void *arg){

   ~~pthread_mutex_lock(&mutex);~~
   printf(“hello ”);
   saidHello = true;
   pthread_cond_signal(&cond);
   ~~pthread_mutex_unlock(&mutex~~);
   return NULL;
}
```

```
void* sayBye(void *arg){

   pthread_mutex_lock(&mutex);
   while(!saidHello) {
      pthread_cond_wait(&mutex, &cond);
   }
   printf(“bye\n”);
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

Why grab a lock to protect signal?
Is this a must?
Yes. Otherwise, we “lost signal”

Example II – hello bye

```
pthread_mutex_t mutex;
pthread_cond_t cond;
bool saidHello = false;
```

```
void* sayHello(void *arg){

   pthread_mutex_lock(&mutex);
   printf("hello ");
   saidHello = true;
   pthread_cond_signal(&cond);
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

```
void* sayBye(void *arg){

   pthread_mutex_lock(&mutex);
   while(!saidHello) {
     ~~pthread_cond_wait(&mutex, &cond);~~
       pthread_mutex_unlock(&mutex);
       pthread_cond_block(&cond);
   }
   printf("bye\n");
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

Why atomically release the lock and block calling thread?

Example II – hello bye

```
pthread_mutex_t mutex;
pthread_cond_t cond;
bool saidHello = false;
```

```
void* sayHello(void *arg){

   pthread_mutex_lock(&mutex);
   printf("hello ");
   saidHello = true;
   pthread_cond_signal(&cond);
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

```
void* sayBye(void *arg){

   pthread_mutex_lock(&mutex);
   while(!saidHello) {
      ~~pthread_cond_wait(&mutex, &cond);~~
      pthread_mutex_unlock(&mutex);
      pthread_cond_block(&cond);
   }
   printf("bye\n");
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```

Why atomically release the lock and block calling thread?
Avoid losing signal.

Example I

```
typedef struct {
  int data[MAX];
  int size;
  pthread_mutex_t mutex;
  pthread_cond_t empty;
  pthread_cond_t full;
} buffer_t;
```

```
buffer_t buf;
int result;
```

```
void* sender(void *arg){

  srandom(time());

  while(1) {
    pthread_mutex_lock(&buf.mutex);
    while(buffer_is_full()) {
      pthread_cond_wait(&buf.empty,
                        &buf.mutex);
    }
    fill_buffer();
    pthread_cond_signal(&buf.full);
    pthread_mutex_unlock(&buf.mutex);
  }
    return NULL;
}
```

```
void* receiver(void *arg){

  srandom(time());

  while(1) {
    pthread_mutex_lock(&buf.mutex);
    while(buffer_is_empty()) {
      pthread_cond_wait(&buf.full,
                        &buf.mutex);

    }
    read_buffer();
    pthread_cond_signal(&buf.empty);
    pthread_mutex_unlock(&buf.mutex);
  }
    return NULL;
}
```

Example III

The unfairness of pthread_mutex_lock

Thread 1	Thread 2	Thread 3
`pthread_mutex_lock(&mu);`	`pthread_mutex_lock(&mu);`	`pthread_mutex_lock(&mu);`
`processing`	*block and wait*	*block and wait*

Example III

The unfairness of pthread_mutex_lock

Thread 1

```
pthread_mutex_lock(&mu);

processing

pthread_mutex_unlock(&mu);
```

Thread 2

```
pthread_mutex_lock(&mu);
```

block and wait

Thread 3

```
pthread_mutex_lock(&mu);
```

block and wait

Example III

The unfairness of pthread_mutex_lock

Thread 1

```
pthread_mutex_lock(&mu);

processing

pthread_mutex_unlock(&mu);
```

Thread 2

```
pthread_mutex_lock(&mu);
```

block and wait

```
processing
```

Thread 3

```
pthread_mutex_lock(&mu);
```

block and wait

Example III

The unfairness of pthread_mutex_lock

Thread 1

```
pthread_mutex_lock(&mu);
processing
pthread_mutex_unlock(&mu);
pthread_mutex_lock(&mu);
```

Thread 2

```
pthread_mutex_lock(&mu);
```

block and wait

```
processing
```

Thread 3

```
pthread_mutex_lock(&mu);
```

block and wait

Example III

The unfairness of pthread_mutex_lock

Thread 1	Thread 2	Thread 3
`pthread_mutex_lock(&mu);`		
		`pthread_mutex_lock(&mu);`
`processing`	`pthread_mutex_lock(&mu);`	*block and wait*
	block and wait	
`pthread_mutex_unlock(&mu);`	`processing`	
`pthread_mutex_lock(&mu);`		
block and wait		

Example III

The unfairness of pthread_mutex_lock

Thread 1

```
pthread_mutex_lock(&mu);

processing

pthread_mutex_unlock(&mu);
pthread_mutex_lock(&mu);
```

block and wait

Thread 2

```
pthread_mutex_lock(&mu);
```

block and wait

```
processing

pthread_mutex_unlock(&mu);
```

Thread 3

```
pthread_mutex_lock(&mu);
```

block and wait

Example III

pthread_mutex_lock does not guarantee fairness

Thread 1	Thread 2	Thread 3
`pthread_mutex_lock(&mu);`		
	`pthread_mutex_lock(&mu);`	`pthread_mutex_lock(&mu);`
`processing`	*block and wait*	*block and wait*
`pthread_mutex_unlock(&mu);`	`processing`	
`pthread_mutex_lock(&mu);`		
block and wait	`pthread_mutex_unlock(&mu);`	
`processing`		

Starving of Thread 3!

Example III

Add fairness to the mutex → FIFO Lock

- A first in first out queue-based locking mechanism
- Locks are granted in the order they are requested

Example III

The unfairness of pthread_mutex_lock

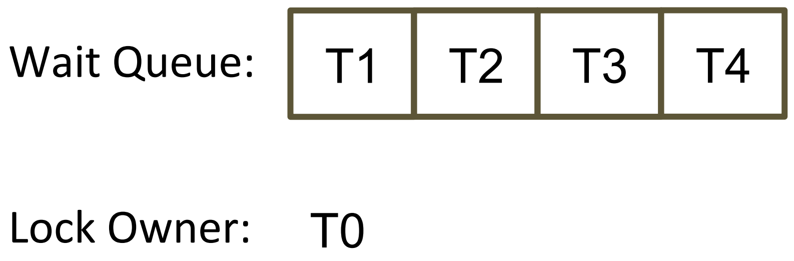
Thread 1	Thread 2	Thread 3
`pthread_mutex_lock(&mu);`		
	`pthread_mutex_lock(&mu);`	`pthread_mutex_lock(&mu);`
`processing`		
	block and wait	*block and wait*
`pthread_mutex_unlock(&mu);`	`processing`	
`pthread_mutex_lock(&mu);`	`pthread_mutex_unlock(&mu);`	
block and wait		
		`processing`

After Thread 2, it should be Thread 3’s turn to get lock.

Example III

Add fairness to the mutex → FIFO Lock

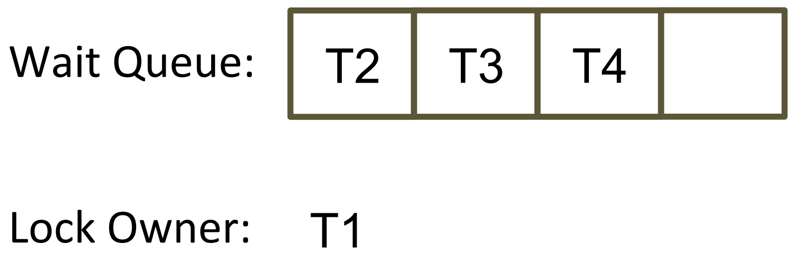
- A first in first out queue-based locking mechanism
- Locks are granted in the order they are requested



Example III

Add fairness to the mutex → FIFO Lock

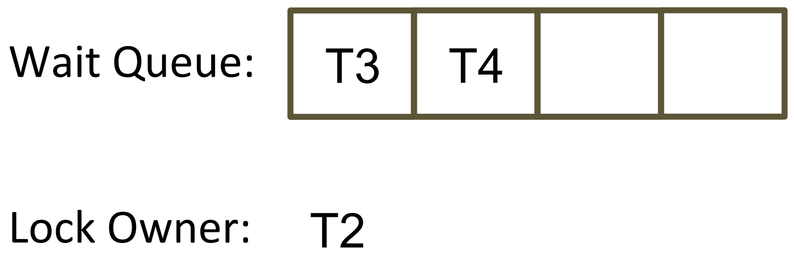
- A first in first out queue-based locking mechanism
- Locks are granted in the order they are requested



Example III

Add fairness to the mutex → FIFO Lock

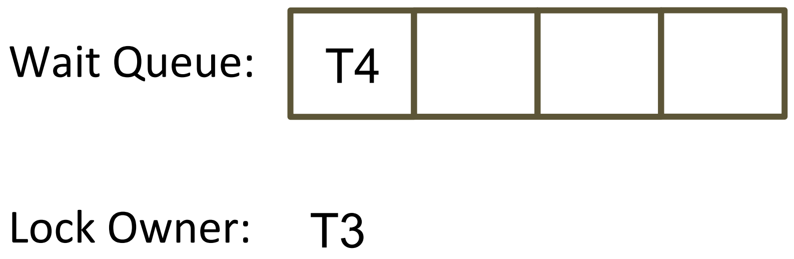
- A first in first out queue-based locking mechanism
- Locks are granted in the order they are requested



Example III

Add fairness to the mutex → FIFO Lock

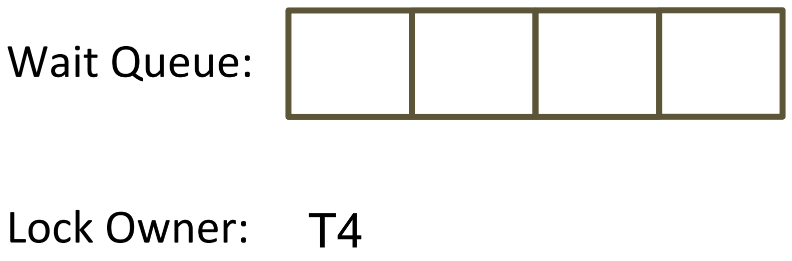
- A first in first out queue-based locking mechanism
- Locks are granted in the order they are requested



Example III

Add fairness to the mutex → FIFO Lock

- A first in first out queue-based locking mechanism
- Locks are granted n the order they are requested



Example III: FIFO Lock

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head;
  node_t *tail;
  bool busy;
} lock_t;
```

$\longrightarrow$ protect access to struct fields

$\}$ FIFO queue is a linked list (keeping pointers to head and tail of the list)

$\searrow$ Track status of the lock. True if granted. False if free

Example III: FIFO Lock

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head;
  node_t *tail;
  bool busy;
} lock_t;
```

```
typedef struct node_t {
  pthread_cond_t cond;
  struct node_t* next;
  int blocked;
} node_t;
```

Allows each thread to block on one linked list node

indicates whether thread should be blocked or not

```
typedef struct node_t {
  pthread_cond_t cond;
  struct node_t* next;
  bool blocked;
} node_t;
```

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head, *tail;
  bool busy;
} lock_t;
```

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(!l->busy) {
    l->busy = true;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
```

Acquire Lock

1. If the lock is unlocked, set the busy bit and return

```
typedef struct node_t {
  pthread_cond_t cond;
  struct node_t* next;
  int blocked;
} node_t;
```

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head, *tail;
  int busy; // 0: free, 1: busy
} lock_t;
```

```
int tthread_fifo_lock(fifo_lock_t *l)
{
  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(!l->busy) {
    l->busy = true;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = true;
  n->next = NULL;
  if(l->head == NULL) {
    l->head = n;
    l->tail = n;
  } else {
    l->tail->next = n;
    l->tail = n;
  }
```

Acquire Lock

1. If the lock is unlocked, set the busy bit and return
2. Otherwise create a node and append it to the linked list. (Blocked is initialized to be 1)

```
typedef struct node_t {
  pthread_cond_t cond;
  struct node_t* next;
  int blocked;
} node_t;
```

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head, *tail;
  int busy; // 0: free, 1: busy
} lock_t;
```

```
int tthread_fifo_lock(fifo_lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(!l->busy) {
    l->busy = true;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = true;
  n->next = NULL;
  if(l->head == NULL) {
    l->head = n;
    l->tail = n;
  } else {
    l->tail->next = n;
    l->tail = n;
  }
  while(n->blocked) {
    pthread_cond_wait(&n->cond, &l->mutex);
  }
```

Acquire Lock

1. If the lock is unlocked, set the busy bit and return
2. Otherwise create a node and append it to the linked list. (Blocked is initialized to be 1)
3. Suspend itself on the cond variable of the created node.

```
typedef struct node_t {
  pthread_cond_t cond;
  struct node_t* next;
  int blocked;
} node_t;
```

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head, *tail;
  int busy; // 0: free, 1: busy
} lock_t;
```

```
int tthread_fifo_lock(fifo_lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = true;
  n->next = NULL;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(n->blocked) {
    pthread_cond_wait(&n->cond, &l->mutex);
  }
```

```
int tthread_fifo_unlock(fifo_lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // no waiters
  if(l->head == NULL) {
    l->busy = 0;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
```

Release Lock

1. If there is no waiter, clear the busy field.

```
typedef struct node_t {
  pthread_cond_t cond;
  struct node_t* next;
  int blocked;
} node_t;
```

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head, *tail;
  int busy; // 0: free, 1: busy
} lock_t;
```

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = true;
  n->next = NULL;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(n->blocked) {
    pthread_cond_wait(&n->cond, &l->mutex);
  }
```

```
int tthread_fifo_unlock(fifo_lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // no waiters
  if(l->head == NULL) {
    l->busy = false;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = false;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

Release Lock

1. If there is no waiters, clear the busy field.
2. Otherwise, clear the blocked field of the first node in the waiting list and wakeup the suspended thread.

```
typedef struct node_t {
  pthread_cond_t cond;
  struct node_t* next;
  int blocked;
} node_t;
```

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head, *tail;
  int busy; // 0: free, 1: busy
} lock_t;
```

```
int tthread_fifo_lock(lock_t *l) {
  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = true;
  n->next = NULL;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(n->blocked)
    pthread_cond_wait(&n->cond, &l->mutex);
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // no waiters
  if(l->head == NULL) {
    l->busy = false;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = false;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

Acquire Lock

4. Remove and free the node from the waiting list

```
lock_t l < busy: 0, head: null, tail: null >,  int global: 0
```

Thread 1

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = 1;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(l->head->blocked) {
    pthread_cond_wait(&l->tail->cond, &l->mutex);
  }
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

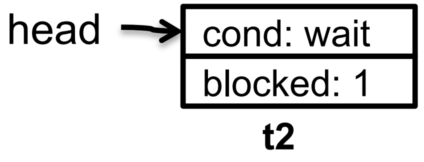
```
lock_t l < busy: 1, head: null, tail: null >,  int global: 0
```

Thread 1

```
tthread_fifo_lock(&l)
```

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = 1;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(l->head->blocked) {
    pthread_cond_wait(&l->tail->cond, &l->mutex);
  }
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 1, head: t2, tail: t2>,  int global: 0
```



Thread 1

Thread 2

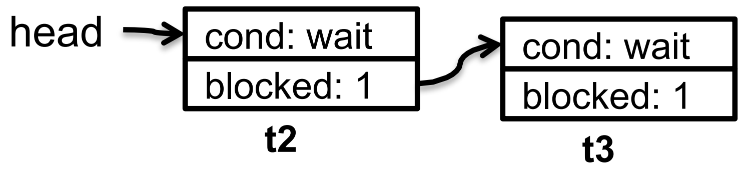
```
tthread_fifo_lock(&l)
```

```
                    tthread_fifo_lock(&l)
```

wait and block

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = 1;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(l->head->blocked) {
    pthread_cond_wait(&l->tail->cond, &l->mutex);
  }
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 1, head: t2, tail: t3>,  int global: 0
```



Thread 1

`tthread_fifo_lock(&l)`

Thread 2

`tthread_fifo_lock(&l)`

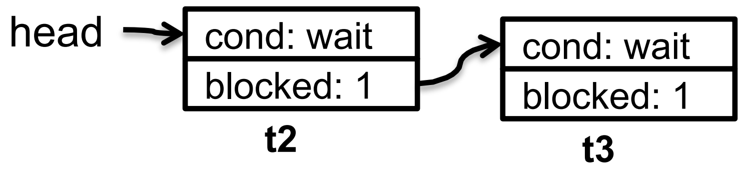
wait and block

Thread 3

`tthread_fifo_lock(&l)`

```c
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = 1;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(l->head->blocked) {
    pthread_cond_wait(&l->tail->cond, &l->mutex);
  }
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 1, head: t2, tail: t3>,  int global: 1
```



Thread 1

Thread 2

Thread 3

```
tthread_fifo_lock(&l)
```

```
                          tthread_fifo_lock(&l)
```

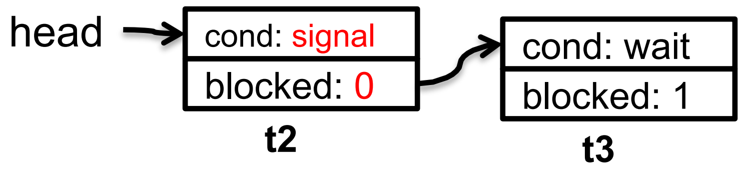
```
 global++
```

wait and block

```
                                       tthread_fifo_lock(&l)
```

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = 1;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(l->head->blocked) {
    pthread_cond_wait(&l->tail->cond, &l->mutex);
  }
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 1, head: t2, tail: t3>,  int global: 1
```



Thread 1

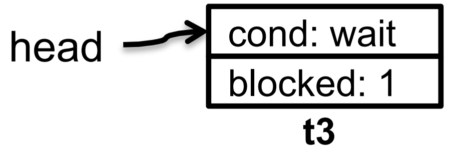
Thread 2

Thread 3

```
tthread_fifo_lock(&l)

                             tthread_fifo_lock(&l)

 global++                    wait and block                  tthread_fifo_lock(&l)


tthread_fifo_unlock(&l)
```

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
   // no waiters
  if(l->head == NULL) {
    l->busy = 0;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = 0;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 1, head: t3, tail: t3>,  int global: 2
```



Thread 1

```
tthread_fifo_lock(&l)

 global++

tthread_fifo_unlock(&l)
```

Thread 2

```
tthread_fifo_lock(&l)
```

wait and block

wakeup

```
global++
```

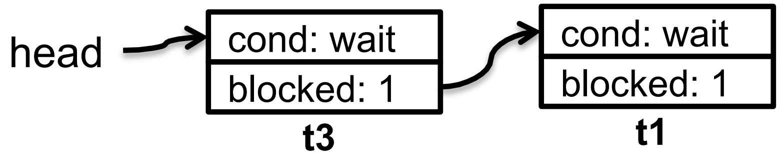
Thread 3

```
tthread_fifo_lock(&l)
```

wait and block

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = 1;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(l->head->blocked) {
    pthread_cond_wait(&l->tail->cond, &l->mutex);
  }
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 1, head: t3, tail: t1>,  int global: 2
```



Thread 1

```
tthread_fifo_lock(&l)

global++

tthread_fifo_unlock(&l)

tthread_fifo_lock(&l)
```

Thread 2

```
tthread_fifo_lock(&l)
```

wait and block

wakeup

```
global++
```

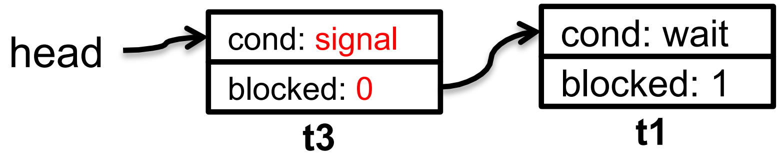
Thread 3

```
tthread_fifo_lock(&l)
```

wait and block

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = 1;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(l->head->blocked) {
    pthread_cond_wait(&l->tail->cond, &l->mutex);
  }
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

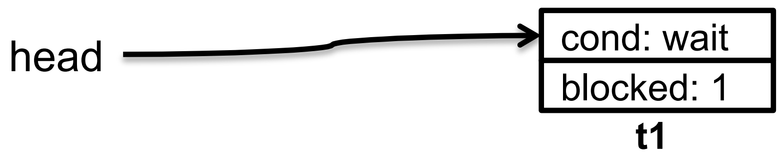
```
lock_t l < busy: 1, head: t3, tail: t1>,  int global: 2
```



```
tthread_fifo_lock(&l)
                         tthread_fifo_lock(&l)
 global++                wait and block            tthread_fifo_lock(&l)

tthread_fifo_unlock(&l)  wakeup                    wait and block
tthread_fifo_lock(&l)    global++
                         tthread_fifo_unlock(&l)
```

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
   // no waiters
  if(l->head == NULL) {
    l->busy = 0;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = 0;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 1, head: t1, tail: t1>,  int global: 3
```



Thread 1

```
tthread_fifo_lock(&l)

 global++

tthread_fifo_unlock(&l)
tthread_fifo_lock(&l)
```
wait and block

Thread 2

```
tthread_fifo_lock(&l)
```
wait and block

wakeup
```
global++
tthread_fifo_unlock(&l)
```

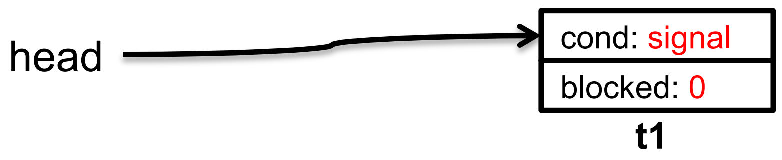
Thread 3

```
tthread_fifo_lock(&l)
```
wait and block

wakeup
```
global++
```

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
   // no waiters
  if(l->head == NULL) {
    l->busy = 0;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = 0;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 1, head: t1, tail: t1>,  int global: 3
```



Thread 1	Thread 2	Thread 3
`tthread_fifo_lock(&l)`		
	`tthread_fifo_lock(&l)`	
`global++`	**wait and block**	`tthread_fifo_lock(&l)`
`tthread_fifo_unlock(&l)`	**wakeup**	**wait and block**
`tthread_fifo_lock(&l)`	`global++`	
wait and block	`tthread_fifo_unlock(&l)`	**wakeup**
		`global++`
		`tthread_fifo_unlock(&l)`

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
   // no waiters
  if(l->head == NULL) {
    l->busy = 0;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = 0;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

`lock_t l < busy: 1, head: null, tail: null>,  int global: 3`

t1

Thread 1	Thread 2	Thread 3
`tthread_fifo_lock(&l)`		
	`tthread_fifo_lock(&l)`	
`global++`	**wait and block**	`tthread_fifo_lock(&l)`
`tthread_fifo_unlock(&l)`	**wakeup**	**wait and block**
`tthread_fifo_lock(&l)`	`global++`	
wait and block	`tthread_fifo_unlock(&l)`	**wakeup**
		`global++`
wakeup		
		`tthread_fifo_unlock(&l)`

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
   // no waiters
  if(l->head == NULL) {
    l->busy = 0;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = 0;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
lock_t l < busy: 0, head: null, tail: null>,  int global: 4
```

t1

Thread 1	Thread 2	Thread 3
`tthread_fifo_lock(&l)`		
	`tthread_fifo_lock(&l)`	
`global++`	**wait and block**	`tthread_fifo_lock(&l)`
`tthread_fifo_unlock(&l)`	**wakeup**	**wait and block**
`tthread_fifo_lock(&l)`	`global++`	
wait and block	`tthread_fifo_unlock(&l)`	**wakeup**
		`global++`
wakeup		
		`tthread_fifo_unlock(&l)`
`global++`		
`tthread_fifo_unlock(&l)`		

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
   // no waiters
  if(l->head == NULL) {
    l->busy = 0;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = 0;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

```
typedef struct node_t {
  pthread_cond_t cond;
  struct node_t* next;
  int blocked;
} node_t;
```

```
typedef struct {
  pthread_mutex_t mutex;
  node_t *head, *tail;
  int busy; // 0: free, 1: busy
} lock_t;
```

```
int tthread_fifo_lock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // lock is free, hold the lock
  if(l->busy == 0) {
    l->busy = 1;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  // lock is busy, suspend on a new cond
  node_t *n = malloc(sizeof(node_t));
  n->blocked = 1;
  if(l->head == NULL) {
    l->head = n;
    l->tail = l->head;
  } else {
    l->tail->next = n;
    l->tail = l->tail->next;
  }
  while(l->head->blocked) {
    pthread_cond_wait(&l->tail->cond, &l->mutex);
  }
  l->head = l->head->next;
  if(l->head == NULL) l->tail = NULL;
  free(n);
  pthread_mutex_unlock(&l->mutex);
  return 0;
```

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  // no waiters
  if(l->head == NULL) {
    l->busy = 0;
    pthread_mutex_unlock(&l->mutex);
    return 0;
  }
  l->head->blocked = 0;
  pthread_cond_signal(&l->head->cond);
  pthread_mutex_unlock(&l->mutex);
  return 0;
}
```

Can we get rid of the list?

```
typedef struct {
  pthread_mutex_t mutex;
  pthread_cond_t cond;
  volatile unsigned long owner, ticket;
} lock_t;
```

Basic Idea

When a thread requests the lock, it will be assigned with a ticket number. The thread needs to wait until its turn is up.

Lock

1. owner: the holder’s ticket number
2. ticket: the ticket number waits to be assigned
3. cond: all waiting threads are blocked on cond

```
typedef struct {
  pthread_mutex_t mutex;
  pthread_cond_t cond;
  volatile unsigned long owner, ticket;
} lock_t;


int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

Acquire a lock

1. Get a ticket number from ticket and update it

```c
typedef struct {
  pthread_mutex_t mutex;
  pthread_cond_t cond;
  volatile unsigned long owner, ticket;
} lock_t;


int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

Acquire a lock

1. Get a ticket number from ticket and update it
2. Check if its turn is up by comparing holder's ticket number with its local ticket number

```
typedef struct {
  pthread_mutex_t mutex;
  pthread_cond_t cond;
  volatile unsigned long owner, ticket;
} lock_t;
```

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  l->owner++;
  pthread_cond_broadcast(&l->cond);
  pthread_mutex_unlock(&l->mutex);
}
```

Release the lock

1. Increate the holder's ticket number to pass the lock the next waiter
2. Wakeup all the waiters

```c
typedef struct {
  pthread_mutex_t mutex;
  pthread_cond_t cond;
  volatile unsigned long owner, ticket;
} lock_t;
```

```c
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```c
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  l->owner++;
  pthread_cond_broadcast(&l->cond);
  pthread_mutex_unlock(&l->mutex);
}
```

Acquire the lock

1. After all waiters wakeup, each one will its local ticket number with the holder's ticket number.
2. Only the thread which has the same ticket number with the owner will hold the lock, all the others will suspend them self again.

```
lock_t l < owner: 0, ticket: 0 >,  int global: 0
```

Thread 1

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```
lock_t l < owner: 0, ticket: 1 >,  int global: 0
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```
lock_t l < owner: 0, ticket: 2 >,  int global: 0
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

Thread 2

```
tthread_fifo_lock(&l)
```

Get ticket 1, wait for owner to be 1

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```
lock_t l < owner: 0, ticket: 3 >,  int global: 0
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

Thread 2

```
tthread_fifo_lock(&l)
```

Get ticket 1, wait for owner to be 1

Thread 3

```
tthread_fifo_lock(&l)
```

Get ticket 2, wait for owner to be 2

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```
lock_t l < owner: 1, ticket: 3 >,  int global: 1
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

Thread 2

```
tthread_fifo_lock(&l)
```

Get ticket 1, wait for owner to be 1

Thread 3

```
tthread_fifo_lock(&l)
```

Get ticket 2, wait for owner to be 2

```
int tthread_fifo_unlock(lock_t *l) {

  pthread_mutex_lock(&l->mutex);
  l->owner++;
  pthread_cond_broadcast(&l->cond);
  pthread_mutex_unlock(&l->mutex);
}
```

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

`lock_t l < owner: 1, ticket: 3 >,  int global: 2`

Thread 1

`tthread_fifo_lock(&l)`

Get ticket 0

`global++`

`tthread_fifo_unlock(&l)`

Pass the lock to next, by updating owner

Thread 2

`tthread_fifo_lock(&l)`

Get ticket 1, wait for owner to be 1

wakeup

`global++`

Thread 3

`tthread_fifo_lock(&l)`

Get ticket 2, wait for owner to be 2

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```
lock_t l < owner: 1, ticket: 4 >,  int global: 2
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

```
tthread_fifo_lock(&l)
```

Get ticket 3, wait for owner to be 3

Thread 2

```
tthread_fifo_lock(&l)
```

Get ticket 1, wait for owner to be 1

wakeup

```
global++
```

Thread 3

```
tthread_fifo_lock(&l)
```

Get ticket 2, wait for owner to be 2

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```
lock_t l < owner: 2, ticket: 4 >,  int global: 2
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

```
tthread_fifo_lock(&l)
```

Get ticket 3, wait for owner to be 3

Thread 2

```
tthread_fifo_lock(&l)
```

Get ticket 1, wait for owner to be 1

wakeup

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

Thread 3

```
tthread_fifo_lock(&l)
```

Get ticket 2, wait for owner to be 2

```
int tthread_fifo_lock(lock_t *l) {

  unsigned long me;

  pthread_mutex_lock(&l->mutex);
  me = l->ticket++;
  while(me != l->owner) {
    pthread_cond_wait(&l->cond, &l->mutex);
  }
  pthread_mutex_unlock(&l->mutex);

  return 0;
}
```

```
lock_t l < owner: 2, ticket: 4 >,  int global: 2
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

```
tthread_fifo_lock(&l)
```

Get ticket 3, wait for owner to be 3

Thread 2

```
tthread_fifo_lock(&l)
```

Get ticket 1, wait for owner to be 1

wakeup

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

Thread 3

```
tthread_fifo_lock(&l)
```

Get ticket 2, wait for owner to be 2

wakeup

```
lock_t l < owner: 3, ticket: 4 >,  int global: 2
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

```
tthread_fifo_lock(&l)
```

Get ticket 3, wait for owner to be 3

Thread 2

```
tthread_fifo_lock(&l)
```

Get ticket 1, wait for owner to be 1

wakeup

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

Thread 3

```
tthread_fifo_lock(&l)
```

Get ticket 2, wait for owner to be 2

wakeup

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

```
lock_t l < owner: 4, ticket: 4 >,  int global: 2
```

Thread 1

```
tthread_fifo_lock(&l)
```

Get ticket 0

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

```
tthread_fifo_lock(&l)
```

Get ticket 3, wait for owner to be 3

wakeup

```
global++
tthread_fifo_unlock(&l)
```

update owner

Thread 2

```
tthread_fifo_lock(&l)
```

Get ticket 1, wait for owner to be 1

wakeup

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner

Thread 3

```
tthread_fifo_lock(&l)
```

Get ticket 2, wait for owner to be 2

wakeup

```
global++
tthread_fifo_unlock(&l)
```

Pass the lock to next, by updating owner