# Sistemas Distribuídos

José Orlando Pereira

Departamento de Informática
Universidade do Minho

# Example: Game

- Generic problem: Waiting for an event in a different thread
- Wait for at least Min players before joining the game:

```
void joinTheGame() {
    ready++;
    while (ready < Min)
        ;
}
```

# Example: Game

- Wait for at least Min and at most Max players before joining the game:

```
void joinTheGame() {
    ready++;
    while (ready < Min || playing >= Max)
        ;
    playing++;          // [illegible]ing
}
```

Race: ready = ready + 1

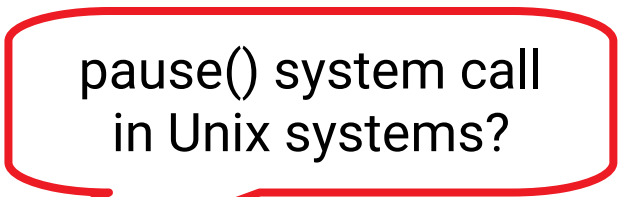
Busy waiting

Race: playing = playing + 1

How many problems with this code?

# Waiting for an event

- Assuming we can ask the OS to suspend and wakeup threads, we solve busy waiting

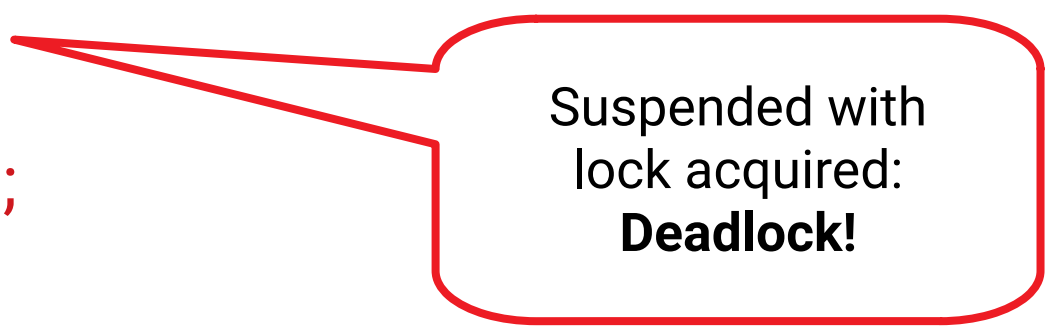



```
void joinTheGame() {
    ready++;
    if (ready < Min || playing >= Max)
        suspendMe();
    playing++;        // playing-- when leaving
    wakeAllOthers();  // also on leaving the game
}
```

# Waiting for an event: 1st attempt

- Add locking:

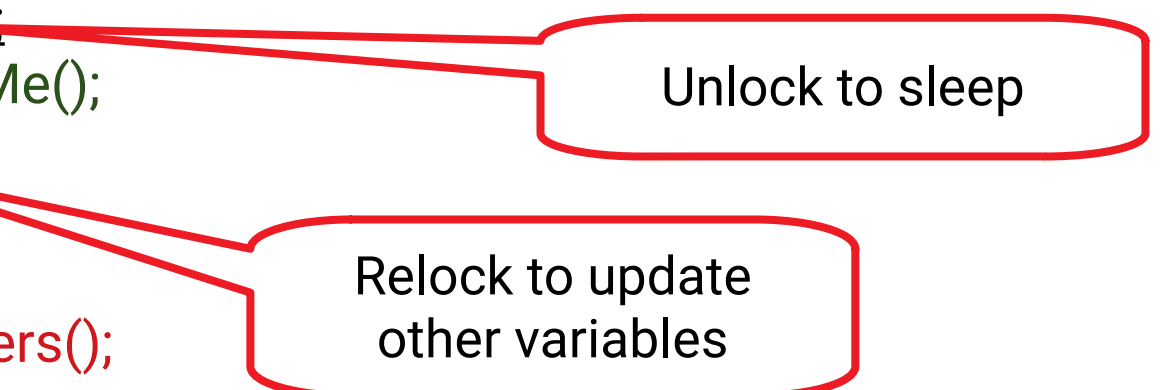
```
void joinTheGame() {
    l.lock();
    ready++;
    if (ready < Min || playing >= Max)
        suspendMe();
    playing++;
    wakeAllOthers();
    l.unlock();
}
```



# Waiting for an event: 2nd attempt

- Unlock while suspended:

```
void joinTheGame() {
    l.lock();
    ready++;
    if (ready < Min || playing >= Max) {
        l.unlock();
        suspendMe();
        l.lock();
    }
    playing++;
    wakeAllOthers();
    l.unlock();
}
```



# Waiting for an event: 2nd attempt

- Player 1:
  - lock
  - ready++;
  - not enough ready, enter “if”
  - unlock

    *(between unlock and suspend)*

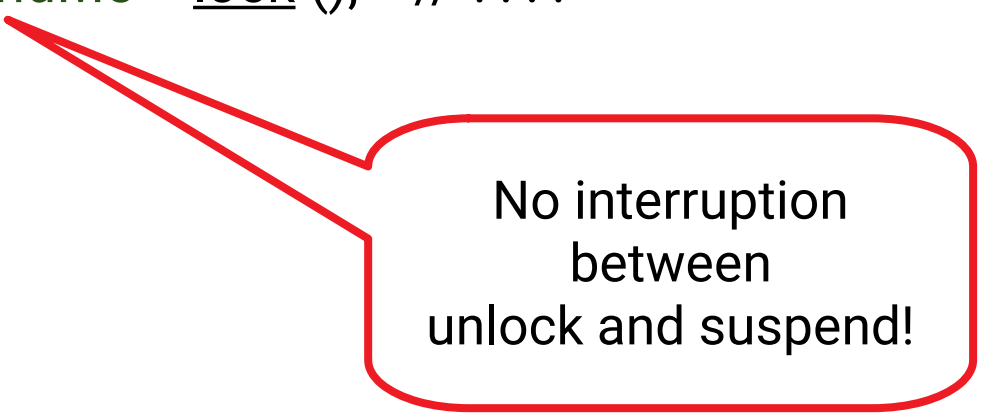
  - suspended…
    possibly forever...
- Player 2:
  - lock…

    … acquired
  - ready++;
  - enough ready, skip “if”
  - wake suspended
  - unlock

# Waiting for an event: 3nd attempt

- Would need something like this:

```
void joinTheGame() {
    l.lock();
    ready++;
    if (ready < Min || playing >= Max) {

        l. unlock + suspendMe + lock ();    // ????

    }
    playing++;
    wakeAllOthers();
    l.unlock();
}
```



# Waiting for events

- Inefficient if the waiting thread is busy polling the condition
- Leads to race conditions / deadlocks if the thread is suspended by the operating system

# Condition Variables

- Atomically suspends the thread and releases the lock:

  Lock l = new ReentrantLock();

  Condition c = l.newCondition();

  c.await(); *// atomically unlocks l and suspends,*
  *// relocks l on wakeup*

- Waking up suspended threads:
  - c.signalAll(); *// all threads*
  - c.signal(); *// one thread*

# Waiting for an event: 3rd attempt

- Atomically unlock and suspend
- Relock when waking up

```
void joinTheGame() {
    l.lock();
    ready++;
    if (ready < Min && playing >= Max)
        c.await();
    playing++;
    c.signalAll();
    l.unlock();
}
```

# Waiting for an event: 3rd attempt

- Player i < Min:
  - lock
  - ready++;
  - not enough ready, enter “if”
  - unlock and suspend
    ...
    ...
  - wakes up!
    (relock)
  - continues!

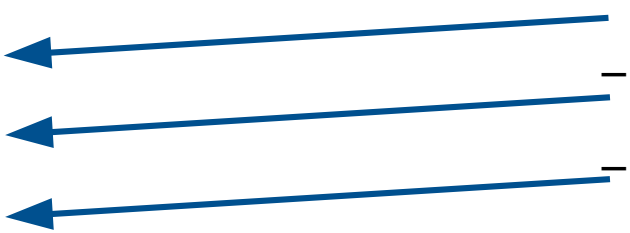
- Player i = Min:
  - lock…
    … acquired
  - ready++;
  - enough ready, skip “if”
  - wake suspended
  - unlock

# Waiting for an event: 3rd attempt

- Players i < Min:
  - lock
  - ready++;
  - not enough ready, enter “if”
  - unlock and suspend

    ...
  - waking up...
  - finally wakes up and gets lock!
  - playing++

- Players Min <= j < Min+Max:
  - player joins (playing++ = 1)
  - ...
  - player joins (playing++ = Max)



**Playing > Max!**

# Waiting for an event: 4th version

- Must always use “while” loop:

```
void joinTheGame() {
    l.lock();
    ready++;
    while (ready < Min || playing >= Max) {
            c.await();
    }
    playing++;
    c.signalAll();
    l.unlock();
}
```

Can also wake up without signal being called! (“Spurious wakeup”)

# Signaling an event

```
void joinTheGame() {
    l.lock();
    ready++;
    while (ready < Min ||
              playing >= Max) {
        c.await();
    }
    ...
    l.unlock();
}
```

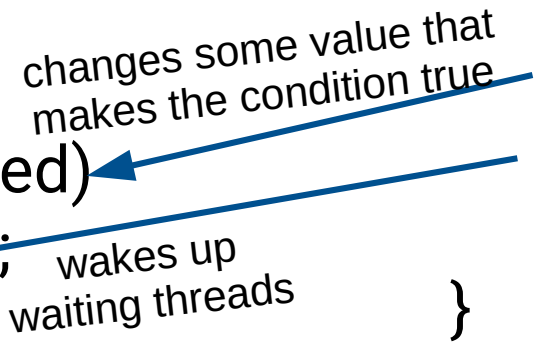
```
void joinTheGame() {
    l.lock();
    ....
    playing++;
    c.signalAll();
    l.unlock();
}
void leaveTheGame() {
    l.lock();
    playing--;
    c.signal();
    l.unlock();
}
```

>1 or not all interested

At most any 1 interested

# Waiting for an event: General case

```
Lock l = new ReentrantLock();
Condition c = l.newCondition();

void waitForEvent() {
    l.lock();
    ...
    while(!happened)
        c.await();
    ...
    l.unlock();
}

void event() {
    l.lock();
    ... // change state
    c.signal() or c.signalAll();
    l.unlock();
}
```



# Conclusions

- Condition variables for efficiently / correctly waiting for events in concurrent programs
- Use await() always within a “while” loop due to:
  - Races
  - Spurious wakeups

# Ordering

- Are the first Max players the ones that join the game?

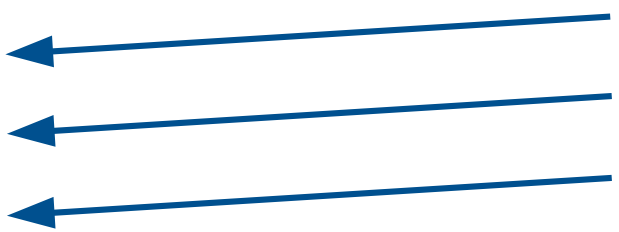
- ReentrantLock has two modes to select the next thread:
  - Default: any waiting thread
  - Fair: Longest waiting thread is favored (but not garanteed...)
- Condition.signal() will wake the longest waiting thread(s), but they need to reacquire the lock

# Waiting for an event: 4th version

- Players i < Min:
  - lock
  - ready++;
  - not enough ready, enter “if”
  - unlock and suspend

    ...
  - waking up...
  - finally wakes up and gets lock!
  - retest playing < Max
    - back to waiting….

- Players Min <= j < Min+Max:
  - player joins (playing++ = 1)
  - ...
  - player joins (playing++ = Max)



Unfair: The first to arrive may not join!

# Waiting for an event: 5th version

- Making the order explicit:

```
void joinTheGame() {
    l.lock();
    ticket = ready++;

    while (ready < Min || playing >= Max || ticket > turn) {
        c.await();
    }
    playing++; turn++;
    c.signalAll();
    l.unlock();
}
```

# Waiting for an event: 5th version

- Making the order explicit:

```
void joinTheGame() {
    l.lock();
    ticket = ready++;
    c.signalAll();
    while (ready < Min || playing >= Max || ticket > turn) {
        c.await();
    }
    playing++; turn++;
    c.signalAll();
    l.unlock();
}
```

# Signaling an event: 5th version

```
void joinTheGame() {
    l.lock();
    ticket = ready++;
    c.signalAll();
    while (ready < Min ||
              playing >= Max ||
              ticket > turn) {
        c.await();
    }
    ...
    l.unlock();
}
```

```
void joinTheGame() {
    l.lock();
    ....
    playing++;
    c.signalAll();
    l.unlock();
}
void leaveTheGame() {
    l.lock();
    playing--;
    c.signalAll();
    l.unlock();
}
```

At most 1 interested, but which one?

# Conclusions

- Entry order is not ensured and when needed has to be provided explicitely
- signalAll():
  - Needed to avoid deadlocks… but wasteful / inefficient
  - How to avoid it?

# Example: Level crossing


(a.k.a. Readers-Writers Lock)



Image from: https://www.deccanherald.com/content/354607/dangerous-rail-crossings.html

# RW lock: Identify conditions

- For a reader:

```
lock() {
    while(there is a writer)
        wait...
}
```

- For a writer:

```
lock() {
    while(there is anyone)
        wait...
}
```

# RW lock: Identify conditions

- For a reader:

```
lock() {
    while(there is a writer)
        wait...
}
```

- For a writer:

```
lock() {
    while(there is anyone)
        wait...
}
```

- How to implement conditions? Add sufficient state:
  - int nr_readers
  - ~~int nr_writers~~ → boolean a_writer

# RW lock: Add state

- For a reader:

```
lock() {
    while(there is a writer)
        wait…
    nr_readers++
}
unlock() {
    nr_readers--
}
```

- For a writer:

```
lock() {
    while(there is anyone)
        wait…
    a_writer = true
}
unlock() {
    a_writer = false
}
```

# RW lock: Write conditions

- For a reader:

```
lock() {
    while(a_writer)
        wait…
    nr_readers++
}
unlock() {
    nr_readers--
}
```

- For a writer:

```
lock() {
    while(a_writer ||
            nr_readers>0)
        wait…
    a_writer = true
}
unlock() {
    a_writer = false
}
```

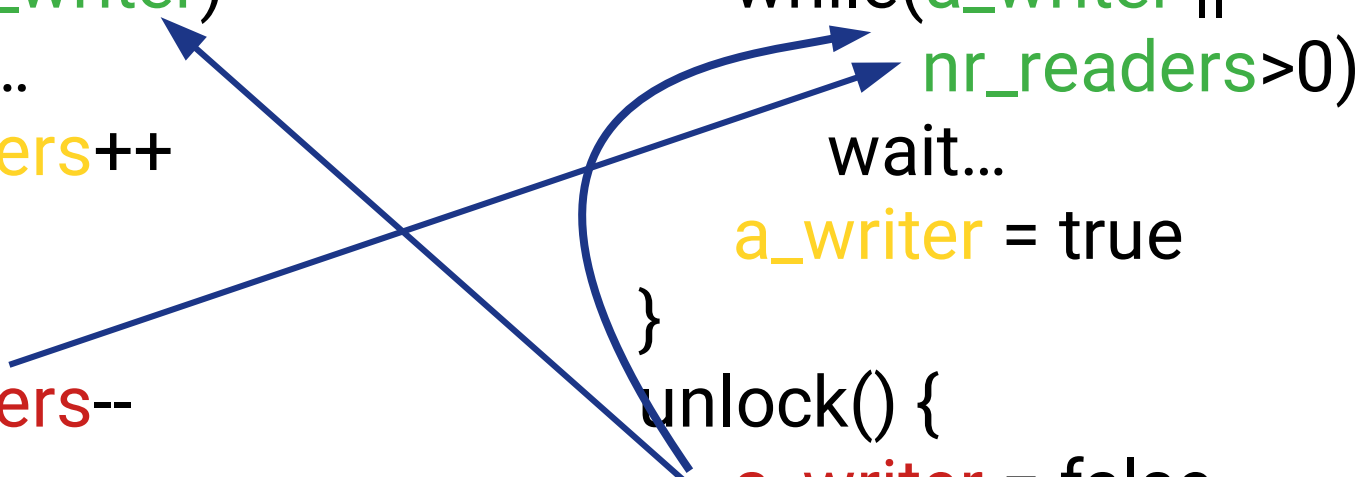
# RW lock: Identify events

- For a reader:

```
lock() {
    while(a_writer)
        wait…
    nr_readers++
}
unlock() {
    nr_readers--
}
```

- For a writer:

```
lock() {
    while(a_writer ||
          nr_readers>0)
        wait…
    a_writer = true
}
unlock() {
    a_writer = false
}
```



# RW lock: Implement events

- For a reader:

```
lock() {
    while(a_writer)
        c.await()
    nr_readers++
}
unlock() {
    nr_readers--
    c.signalAll()
}
```

- For a writer:

```
lock() {
    while(a_writer ||
            nr_readers>0)
        c.await()
    a_writer = true
}
unlock() {
    a_writer = false
    c.signalAll()
}
```

# RW lock: Add locks

```
void readLock() {
    l.lock();
    while(a_writer)
        c.await();
    nr_readers++;
    l.unlock();
}
void readUnlock() {
    l.lock();
    nr_readers--;
    c.signalAll();
    l.unlock();
}
```

```
void writeLock() {
    l.lock();
    while(a_writer ||
            nr_readers>0)
            c.await();
    a_writer = true;
    l.unlock();
}
void writeUnlock() {
    l.lock();
    a_writer = false;
    c.signalAll();
    l.unlock();
}
```

# RW lock: Reduce wakeups

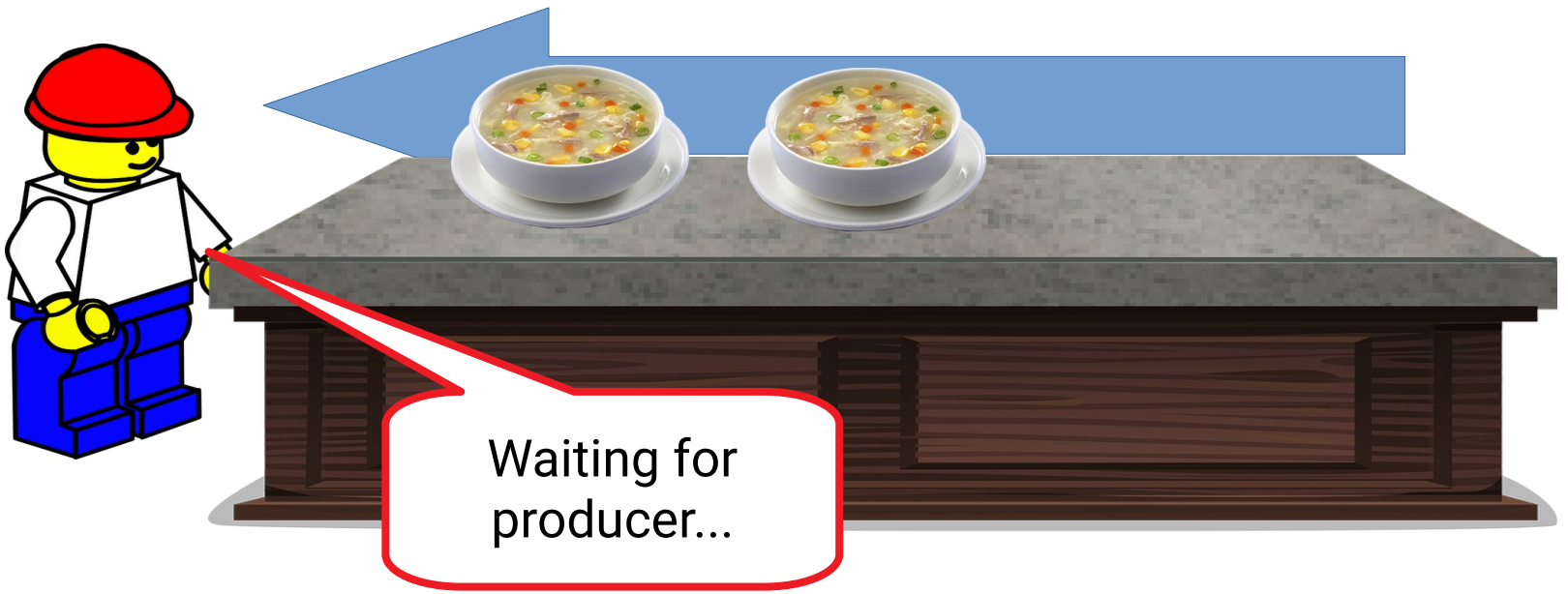
```
void readLock() {
    l.lock();
    while(a_writer)
        c.await();
    nr_readers++;
    l.unlock();
}
void readUnlock() {
    l.lock();
    nr_readers--;
    if (nr_readers==0) c.signal();
    l.unlock();
}
```

```
void writeLock() {
    l.lock();
    while(a_writer ||
            nr_readers>0)
            c.await();
    a_writer = true;
    l.unlock();
}
void writeUnlock() {
    l.lock();
    a_writer = false;
    c.signalAll();
    l.unlock();
}
```

# Example: Soup counter

(a.k.a. Bounded Buffer)

# Blocking consumer



# Bounded buffer: blocking consumer

```
Lock l = new ReentrantLock();
Condition c = l.newCondition();
Queue<Object> q = …;

Object get() {
    l.lock();

    while(q.isEmpty())
        c.await();
    s = q.remove();
    l.unlock();
}
```

```
void put(Object s) {
    l.lock();
    q.add(s);
    c.signalAll();
    l.unlock();
}
```

changes some value that makes the condition true

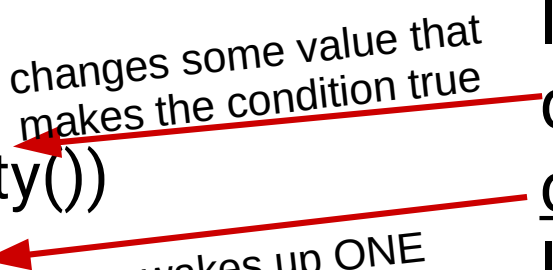
wakes up waiting threads

Why signal ALL if only one continues?

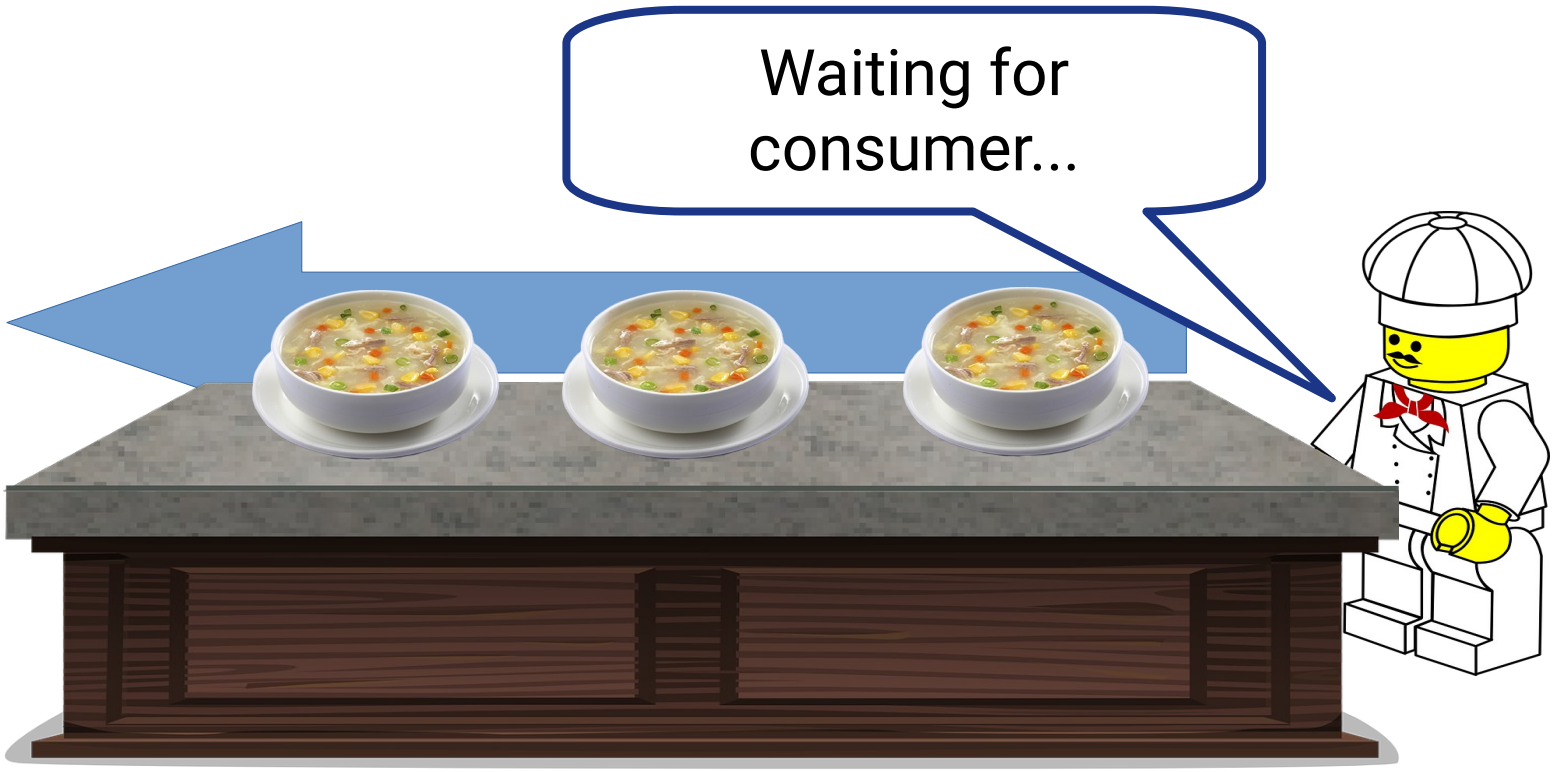
# Bounded buffer: blocking consumer

```
Lock l = new ReentrantLock();
Condition c = l.newCondition();
Queue<Object> q = …;

Object get() {
    l.lock();

    while(q.isEmpty())
        c.await();
    s = q.remove();
    l.unlock();
}
```

```
void put(Object s) {
    l.lock();
    q.add(s);
    c.signal();
    l.unlock();
}
```



# Blocking producer



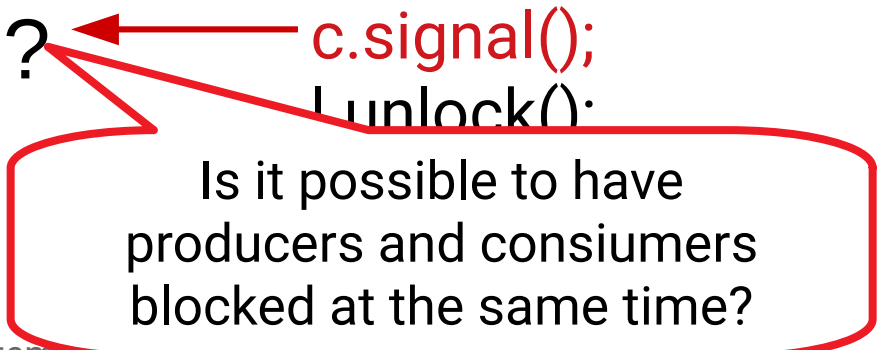
# Bounded buffer: blocking producer

```
Lock l = new ReentrantLock();
Condition c = l.newCondition();
Queue<Object> q = …;

Object get() {
    l.lock();
    s = q.remove();
    c.signal();
    l.unlock();
}
```

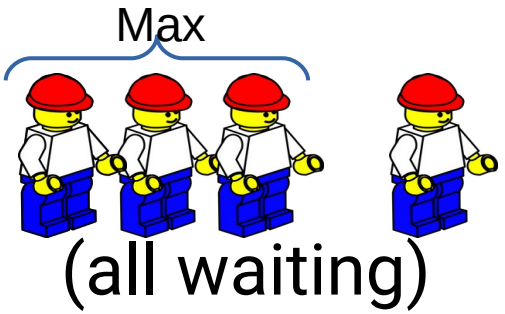
```
void put(Object s) {
    l.lock();

    while(q.size()>=Max)
            c.await()
    q.add(s);
    l.unlock();
}
```

# Bounded buffer: blocking both

```
Lock l = new ReentrantLock();
Condition c = l.newCondition();
Queue<Object> q = …;

Object get() {
    l.lock();
    while(q.isEmpty())
        c.await();
    s = q.remove();
    c.signal();
    l.unlock();
}

void put(Object s) {
    l.lock();
    while(q.size()>=Max)
        c.await()
    q.add(s);
    c.signal();
    l.unlock();
}
```

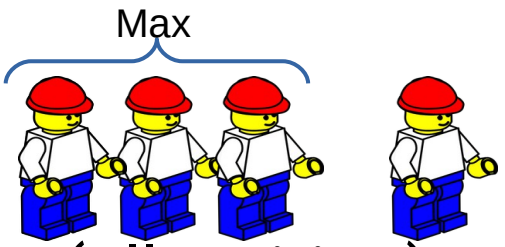


# Bounded buffer

- 

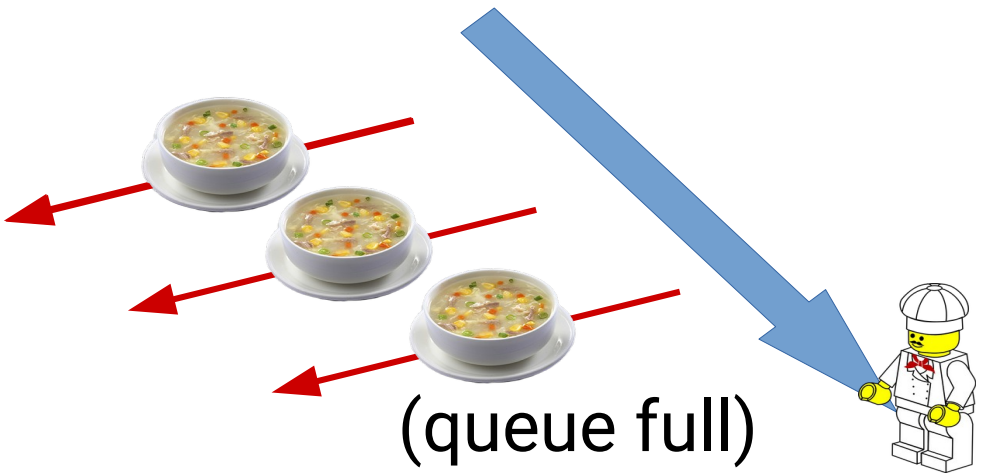

- Buffer of size Max
- More than Max consumers waiting…
- All producers busy elsewhere….

# Bounded buffer

- 

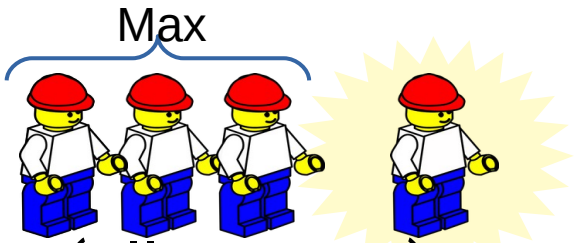
(all waiting)

(3 waiting)
(2 waiting)
(1 waiting)


(queue full)

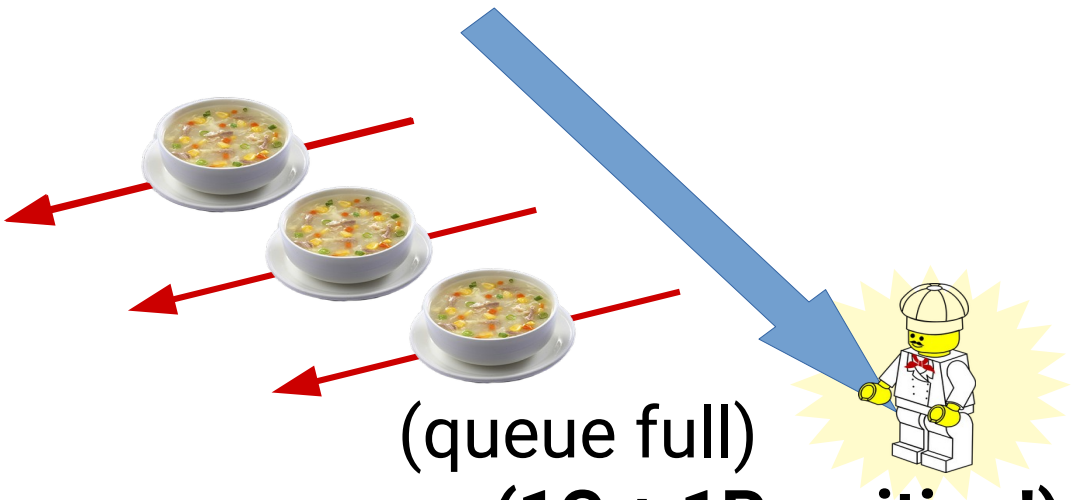
- Producer tries to put more than Max and blocks

# Bounded buffer

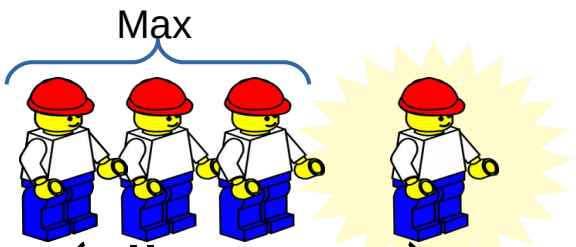
- 

(all waiting)

(3 waiting)
(2 waiting)
(1 waiting)

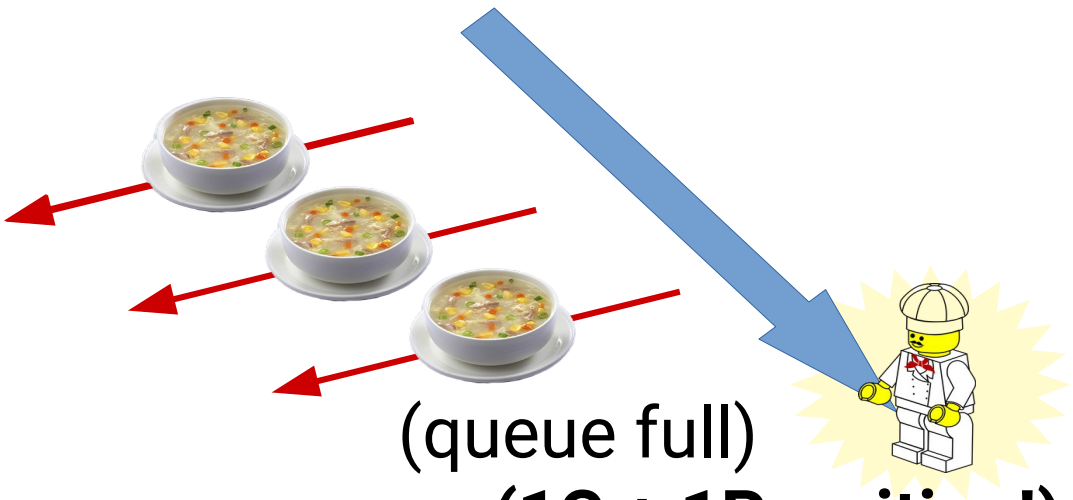

(queue full)
**(1C + 1P waiting!)**

# Bounded buffer

- 

(all waiting)

(3 waiting)
(2 waiting)
(1 waiting)


(queue full)
**(1C + 1P waiting!)**

-  signal() wakes **Consumer** or Producer?

**Deadlock**

# Bounded buffer

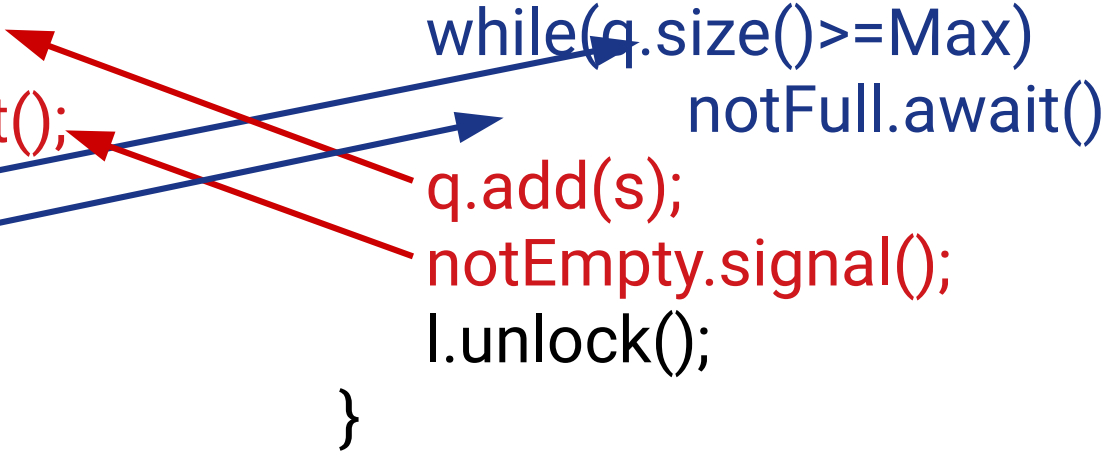
- This is a general problem with different conditions and the same condition variable
- Workaround: Use signalAll()
  - Inefficient (“thundering herd”)
  - This was the only solution with Java “synchronized” monitors (with notifyAll())

# Bounded buffer: 2 condition variables

```
Lock l = new ReentrantLock();
Condition notEmpty = l.newCondition();
Condition notFull = l.newCondition();
Queue<Object> q = …;
```

```
Object get() {
    l.lock();
    while(q.isEmpty())
        notEmpty.await();
    q.remove();
    notFull.signal();
    l.unlock();
}
```

```
void put(Object s) {
    l.lock();
    while(q.size()>=Max)
        notFull.await()
    q.add(s);
    notEmpty.signal();
    l.unlock();
}
```



# Summary

- Using multiple condition variables for the same lock reduces the need to use signalAll()
- But… not easy to be sure!!!

- “Bounded buffer” is an important building block for concurrent programs:
  - Unix *pipes*
  - *Sockets* in distributed programs

# RW lock: Fairness

- Will readers and writers eventually access the critical section?

# RW lock: Identify conditions

- For a reader:

```
lock() {
    while(there is a writer
    inside or waiting)
        wait...
}
```

- For a writer:

```
lock() {
    while(there is anyone)
        wait...
}
```

- How to implement conditions? Add sufficient state:
  - int nr_readers
  - ~~int nr_writers~~ → boolean a_writer
  - int waiting

# RW lock: Add state and conditions

- For a reader:

```
lock() {
    while(writer inside
            || waiting>0)
        wait…
    nr_readers++
}
unlock() {
    nr_readers--
}
```

- For a writer:

```
lock() {
    waiting++
    while(there is anyone)
            wait…
    a_writer = true
    waiting--
}
unlock() {
    a_writer = false
}
```

# RW lock: Implement events

```
lock() {
    while(a_writer ||
            waiting > 0)
        c.await()
    nr_readers++
}
unlock() {
    nr_readers--
    c.signalAll()
}
```

signal?

```
lock() {
    waiting++
    while(a_writer ||
            nr_readers>0)
        c.await()
    a_writer = true
    waiting--
}
unlock() {
    a_writer = false
    c.signalAll()
}
```

No.
This makes it always false.

# RW lock: Reduce wakeups

```
void readLock() {
    l.lock();
    while(a_writer ||
            waiting>0)
            c.await();
    nr_readers++;
    l.unlock();
}
void readUnlock() {
    l.lock();
    nr_readers--;
    if (nr_readers==0) c.signalAll();
    l.unlock();
}
```

Cannot be optimized to c.signal()!

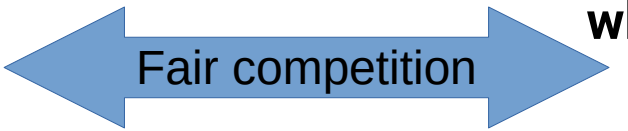
```
void writeLock() {
    l.lock();
    waiting++;
    while(a_writer ||
            nr_readers>0)
            c.await();
    a_writer = true;
    waiting--;
    l.unlock();
}
void writeUnlock() {
    l.lock();
    a_writer = false;
    c.signalAll();
    l.unlock();
}
```

# RW lock: Fairness

- First solution:
  - Infinite stream of readers denies access to writers
- Second solution:
  - Infinite stream of writers denies access to readers
- Ideally:
  - Both get a fair chance, even when faced with a infinite stream of competitors

# Reader-Writer lock: Fair solution

```
void readLock() {
    l.lock();
    while(a_writer)
        c.await();
    nr_readers++;
    l.unlock();
}
void readUnlock() {
    l.lock();
    nr_readers--;
    if (nr_readers==0) c.signalAll();
    l.unlock();
}
```

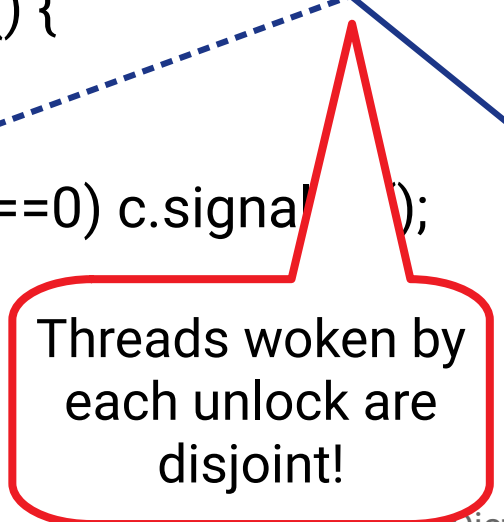



- 
```
void writeLock() {
    l.lock();
    while(a_writer)
        c.await();
    a_writer = true;
    while(nr_readers>0)
        c.await();
    l.unlock();
}
void writeUnlock() {
    l.lock();
    a_writer = false;
    c.signalAll();
    l.unlock();
}
```

# Reader-Writer lock: Rethink signals

```
void readLock() {
    l.lock();
    while(a_writer)
        c.await();
    nr_readers++;
    l.unlock();
}
void readUnlock() {
    l.lock();
    nr_readers--;
    if (nr_readers==0) c.signal();
    l.unlock();
}
```

```
void writeLock() {
    l.lock();
    while(a_writer)
        c.await();
    a_writer = true;
    while(nr_readers>0)
        c.await();
    l.unlock();
}
void writeUnlock() {
    l.lock();
    a_writer = false;
    c.signalAll();
    l.unlock();
}
```



# Reader-Writer lock: 2 condition variables

```
void readLock() {
    l.lock();
    while(a_writer)
        cw.await();
    nr_readers++;
    l.unlock();
}
void readUnlock() {
    l.lock();
    nr_readers--;
    if (nr_readers==0) cr.signal();
    l.unlock();
}
```

```
void writeLock() {
    l.lock();
    while(a_writer)
        cw.await();
    a_writer = true;
    while(nr_readers>0)
        cr.await();
    l.unlock();
}
void writeUnlock() {
    l.lock();
    a_writer = false;
    cw.signalAll();
    l.unlock();
}
```

Can be optimized to c.signal()!

# j.u.c Conditions vs Monitors

- class C {

There is a hidden “condition” in each object used by “wait()/notifyAll()”

```
synchronized public void m1() {
        while(…) wait();
}

synchronized public void m2() {
        notifyAll();
}
}
```

- class C {

```
private Lock l =
        new ReentrantLock();
private Condition c =
        l.newCondition();
public void m1() {
        try { l.lock();
            while(…) c.await()
        } finally { l.unlock(); }
}
public void m2() {
        try { l.lock();
            c.signalAll();
        } finally { l.unlock(); }
}
```

Equivalent code (aproximately...)

# j.u.c. Conditions vs Monitors

- Main differences:
  - One implicit condition for each lock
    vs.
    Many j.u.c. conditions for the same lock
    - Avoids signalAll()
  - Threads waiting for a condition wakeup in any order
    vs.
    Threads waiting for a j.u.c. Condition obtained from a ReentrantLock wakeup in FIFO order (but may not aquire lock in FIFO order...)