CS 333
Introduction to Operating Systems

Class 5 – Semaphores and Classical Synchronization Problems

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An Example Synchronization Problem

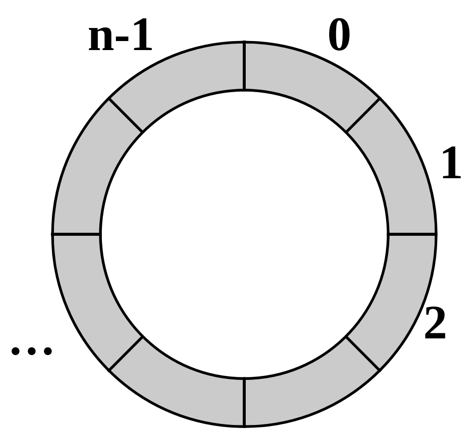
The Producer-Consumer Problem

- **An example of the pipelined model**
  - One thread produces data items
  - Another thread consumes them
- **Use a bounded buffer between the threads**
- **The buffer is a shared resource**
  - Code that manipulates it is a critical section
- **Must suspend the producer thread if the buffer is full**
- **Must suspend the consumer thread if the buffer is empty**

Is this busy-waiting solution correct?

```
thread producer {
    while(1){
      // Produce char c
      while (count==n) {
        no_op
      }
      buf[InP] = c
      InP = InP + 1 mod n
      count++
    }
}
```

```
thread consumer {
    while(1){
      while (count==0) {
        no_op
      }
      c = buf[OutP]
      OutP = OutP + 1 mod n
      count--
      // Consume char
    }
}
```




```
Global variables:
    char buf[n]
    int InP = 0   // place to add
    int OutP = 0  // place to get
    int count
```

This code is incorrect!

- **The "count" variable can be corrupted:**
  - Increments or decrements may be lost!
  - Possible Consequences:
    - **Both threads may spin forever**
    - **Buffer contents may be over-written**
- ***What is this problem called?***

This code is incorrect!

- **The "count" variable can be corrupted:**
  - Increments or decrements may be lost!
  - Possible Consequences:
    - **Both threads may sleep forever**
    - **Buffer contents may be over-written**

- ***What is this problem called?*** ***Race Condition***

- **Code that manipulates count must be made into a *???* and protected using *???***

This code is incorrect!

- **The "count" variable can be corrupted:**
  - Increments or decrements may be lost!
  - Possible Consequences:
    - **Both threads may sleep forever**
    - **Buffer contents may be over-written**
- ***What is this problem called?*** ***Race Condition***
- **Code that manipulates count must be made into a *critical section* and protected using *mutual exclusion!***

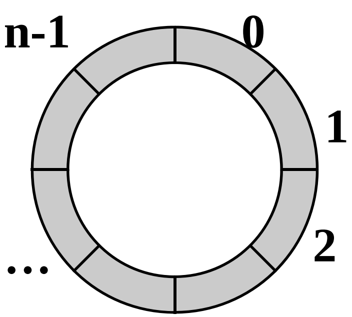
Some more problems with this code

- **What if buffer is full?**
  - Producer will busy-wait
  - On a single CPU system the consumer will not be able to empty the buffer
- **What if buffer is empty?**
  - Consumer will busy-wait
  - On a single CPU system the producer will not be able to fill the buffer
- **We need a solution based on blocking!**

Producer/Consumer with Blocking – 1st attempt

```
thread producer {
  while(1) {
    // Produce char c
    if (count==n) {
      sleep(full)
    }
    buf[InP] = c;
    InP = InP + 1 mod n
    count++
    if (count == 1)
      wakeup(empty)
    }
 }
```

```
thread consumer {
  while(1) {
    if(count==0) {
      sleep(empty)
    }
    c = buf[OutP]
    OutP = OutP + 1 mod n
    count--;
    if (count == n-1)
      wakeup(full)
    // Consume char
  }
}
```

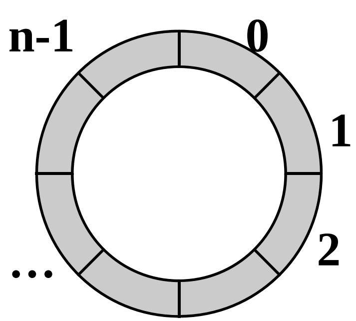



```
Global variables:
    char buf[n]
    int InP = 0   // place to add
    int OutP = 0  // place to get
    int count
```

Use a mutex to fix the race condition in this code

```
thread producer {
 while(1) {
   // Produce char c
   if (count==n) {
     sleep(full)
   }
   buf[InP] = c;
   InP = InP + 1 mod n
   count++
   if (count == 1)
     wakeup(empty)
   }
 }
```

```
thread consumer {
 while(1) {
   if(count==0) {
     sleep(empty)
   }
   c = buf[OutP]
   OutP = OutP + 1 mod n
   count--;
   if (count == n-1)
     wakeup(full)
   // Consume char
 }
}
```




```
Global variables:
    char buf[n]
    int InP = 0    // place to add
    int OutP = 0   // place to get
    int count
```

Problems

- Sleeping while holding the mutex causes deadlock !
- Releasing the mutex then sleeping opens up a window during which a context switch might occur … again risking deadlock
- How can we release the mutex and sleep in a single atomic operation?
- We need a more powerful synchronization primitive

Semaphores

- **An abstract data type that can be used for condition synchronization and mutual exclusion**

What is the difference between mutual exclusion and condition synchronization?

Semaphores

- **An abstract data type that can be used for condition synchronization and mutual exclusion**

- **Condition synchronization**
  - wait until condition holds before proceeding
  - signal when condition holds so others may proceed

- **Mutual exclusion**
  - only one at a time in a critical section

Semaphores

- **An abstract data type**
  - containing an integer variable (S)
  - Two operations: Wait (S) and Signal (S)
- **Alternative names for the two operations**
  - *Wait(S) = Down(S) = P(S)*
  - *Signal(S) = Up(S) = V(S)*
- **Blitz names its semaphore operations Down and Up**

Classical Definition of Wait and Signal

```
Wait(S)
  {
   while S <= 0 do noop;  /* busy wait! */
   S = S – 1;             /* S >= 0 */
  }

Signal (S)
  {
   S = S + 1;
  }
```

Problems with classical definition

- **Waiting threads hold the CPU**
  - Waste of time in single CPU systems
  - Required preemption to avoid deadlock

Blocking implementation of semaphores

Semaphore S has a value, S.val, and a thread list, S.list.

Wait (S)

```
    S.val = S.val - 1
    If S.val < 0                           /* negative value of S.val */
      {   add calling thread to S.list;    /* is # waiting threads */
          block;                           /* sleep */
      }
```

Signal (S)

```
    S.val = S.val + 1
    If S.val <= 0
      {   remove a thread T from S.list;
          wakeup (T);
      }
```

Implementing semaphores

- **Wait () and Signal () are assumed to be atomic**

How can we ensure that they are atomic?

Implementing semaphores

- **Wait () and Signal () are assumed to be atomic**

  How can we ensure that they are atomic?

- **Implement Wait() and Signal() as system calls?**
  - how can the kernel ensure Wait() and Signal() are completed atomically?
  - Same solutions as before
    - **Disable interrupts, or**
    - **Use TSL-based mutex**

Semaphores with interrupt disabling

```
struct semaphore {
        int val;
        list L;
      }
```

```
Wait(semaphore sem)
  DISABLE_INTS
    sem.val--
    if (sem.val < 0){
      add thread to sem.L
      sleep(thread)
    }
  ENABLE_INTS
```

```
Signal(semaphore sem)
  DISABLE_INTS
    sem.val++
    if (sem.val <= 0) {
      th = remove next
         thread from sem.L
      wakeup(th)
    }
  ENABLE_INTS
```

Semaphores with interrupt disabling

```
struct semaphore {
          int val;
          list L;
        }
```

```
Wait(semaphore sem)
  DISABLE_INTS
    sem.val--
    if (sem.val < 0){
      add thread to sem.L
      sleep(thread)
    }
  ENABLE_INTS
```

```
Signal(semaphore sem)
  DISABLE_INTS
    sem.val++
    if (sem.val <= 0) {
      th = remove next
         thread from sem.L
      wakeup(th)
    }
  ENABLE_INTS
```

Blitz code for Semaphore.wait

```
method Wait ()
   var oldIntStat: int
   oldIntStat = SetInterruptsTo (DISABLED)
   if count == 0x80000000
        FatalError ("Semaphore count underflowed during 'Wait‘
        operation")
   EndIf
   count = count – 1
   if count < 0 waitingThreads.AddToEnd (currentThread)
        currentThread.Sleep ()
   endIf
   oldIntStat = SetInterruptsTo (oldIntStat)
endMethod
```

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   count = count – 1
   if count < 0 waitingThreads.AddToEnd (currentThread)
        currentThread.Sleep ()
   endIf
   oldIntStat = SetInterruptsTo (oldIntStat)
endMethod
```

But what is `currentThread.Sleep ()`?

- **If sleep stops a thread from executing, how, where, and when does it return?**
  - which thread enables interrupts following sleep?
  - the thread that called sleep shouldn't return until another thread has called signal !
  - … but how does that other thread get to run?
  - … where exactly does the thread switch occur?
- **Trace down through the Blitz code until you find a call to switch()**
  - Switch is called in one thread but returns in another!
  - See where registers are saved and restored

Look at the following Blitz source code

- **Thread.c**
  - Thread.Sleep ()
  - Run (nextThread)

- **Switch.s**
  - Switch (prevThread, nextThread)

Blitz code for Semaphore.signal

```
method Signal ()
   var oldIntStat: int
   t: ptr to Thread
   oldIntStat = SetInterruptsTo (DISABLED)
   if count == 0x7fffffff
        FatalError ("Semaphore count overflowed during
        'Signal' operation")
   endIf
   count = count + 1
   if count <= 0
        t = waitingThreads.Remove ()
        t.status = READY
        readyList.AddToEnd (t)
   endIf
   oldIntStat = SetInterruptsTo (oldIntStat)
endMethod
```

Blitz code for Semaphore.signal

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method Signal ()
   var oldIntStat: int
   t: ptr to Thread
   oldIntStat = SetInterruptsTo (DISABLED)
   if count == 0x7fffffff
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   endIf
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   count = count + 1
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endMethod
```

Blitz code for Semaphore.signal

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method Signal ()
   var oldIntStat: int
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   if count == 0x7fffffff
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   endIf
   count = count + 1
   if count <= 0
        t = waitingThreads.Remove ()
        t.status = READY
        readyList.AddToEnd (t)
   endIf
   oldIntStat = SetInterruptsTo (oldIntStat)
endMethod
```

Semaphores using atomic instructions

- **Implementing semaphores with interrupt disabling only works on uni-processors**
  - What should we do on a multiprocessor?

- **As we saw earlier, hardware provides special atomic instructions for synchronization**
  - test and set lock (TSL)
  - compare and swap (CAS)
  - etc

- **Semaphore can be built using atomic instructions**
  1. build mutex locks from atomic instructions
  2. build semaphores from mutex locks

Building *spinning* mutex locks using TSL

```
Mutex_lock:
    TSL REGISTER,MUTEX       | copy mutex to register and set mutex to 1
    CMP REGISTER,#0          | was mutex zero?
    JZE ok                   | if it was zero, mutex is unlocked, so return
    JMP mutex_lock           | try again
 Ok: RET                     | return to caller; enter critical section

 Mutex_unlock:
    MOVE MUTEX,#0            | store a 0 in mutex
    RET                      | return to caller
```

Using Mutex Locks to Build Semaphores

- How would you modify the Blitz code to do this?

What if you had a blocking mutex lock?

Problem: Implement a counting semaphore

Up ()

Down ()

...using just Mutex locks

- Goal: Make use of the mutex lock's blocking behavior rather than reimplementing it for the semaphore operations

How about this solution?

```
var cnt: int = 0              -- Signal count
var m1: Mutex = unlocked -- Protects access to "cnt"
    m2: Mutex = locked    -- Locked when waiting
```

Down ():

```
  Lock(m1)
  cnt = cnt – 1
  if cnt<0
    Lock(m2)
    Unlock(m1)
  else
    Unlock(m1)
  endIf
```

Up():

```
  Lock(m1)
  cnt = cnt + 1
  if cnt<=0
    Unlock(m2)
  endIf
  Unlock(m1)
```

How about this solution?

```
var cnt: int = 0             -- Signal count
var m1: Mutex = unlocked -- Protects access to "cnt"
    m2: Mutex = locked    -- Locked when waiting
```

Down ():

```
Lock(m1)
cnt = cnt - 1
if cnt<0
   Lock(m2)
   Unlock(m1)
else
   Unlock(m1)
endIf
```

Up():

```
Lock(m1)
cnt = cnt + 1
if cnt<=0
   Unlock(m2)
endIf
Unlock(m1)
```

Contains a Deadlock!

How about this solution then?

```
var cnt: int = 0            -- Signal count
var m1: Mutex = unlocked -- Protects access to "cnt"
    m2: Mutex = locked   -- Locked when waiting
```

Down ():

```
Lock(m1)
cnt = cnt – 1
if cnt<0
  Unlock(m1)
  Lock(m2)
else
  Unlock(m1)
endIf
```

Up():

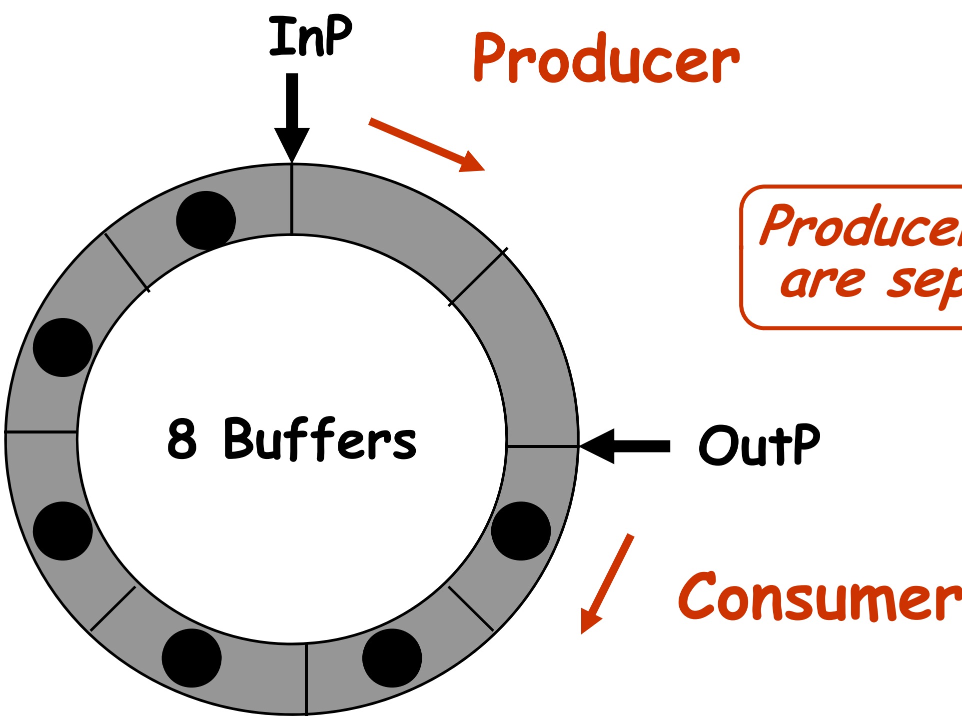
```
Lock(m1)
cnt = cnt + 1
if cnt<=0
  Unlock(m2)
endIf
Unlock(m1)
```

Classical Synchronization problems

- Producer Consumer (bounded buffer)
- Dining philosophers
- Sleeping barber
- Readers and writers

Producer consumer problem

- Also known as the bounded buffer problem

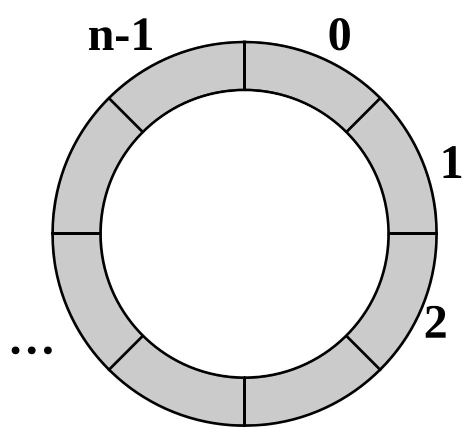


Producer and consumer are separate threads

Is this a valid solution?

```
thread producer {
    while(1){
      // Produce char c
      while (count==n) {
        no_op
      }
      buf[InP] = c
      InP = InP + 1 mod n
      count++
    }
}
```

```
thread consumer {
    while(1){
      while (count==0) {
        no_op
      }
      c = buf[OutP]
      OutP = OutP + 1 mod n
      count--
      // Consume char
    }
}
```




```
Global variables:
    char buf[n]
    int InP = 0    // place to add
    int OutP = 0   // place to get
    int count
```

Does this solution work?

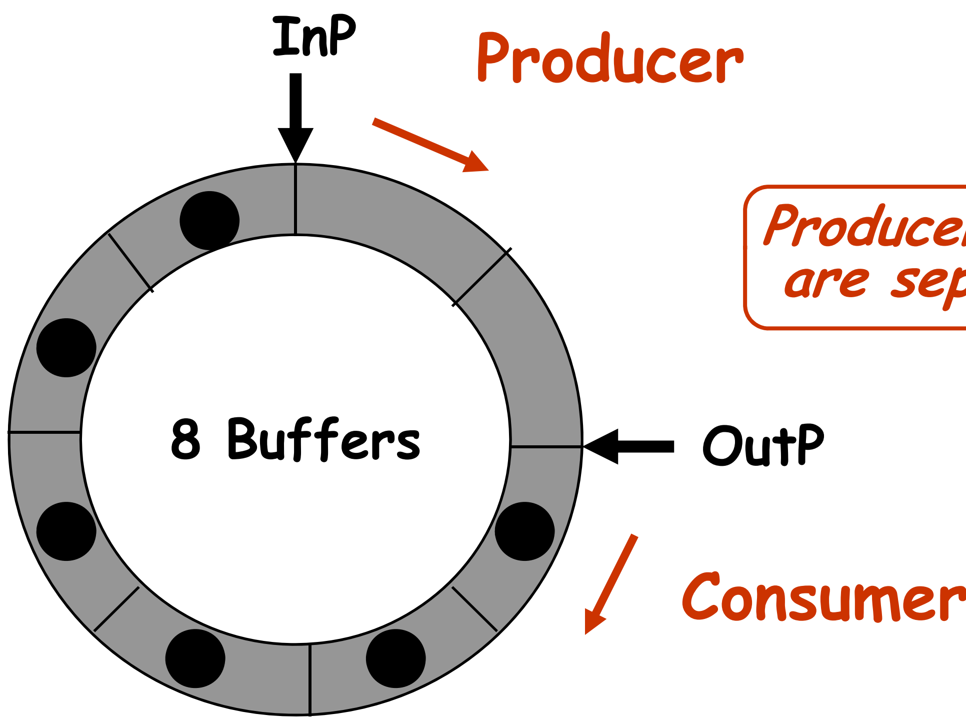
```
Global variables
  semaphore full_buffs = 0;
  semaphore empty_buffs = n;
  char buff[n];
  int InP, OutP;
```

```
thread producer {
  while(1){
    // Produce char c...
    down(empty_buffs)
    buf[InP] = c
    InP = InP + 1 mod n
    up(full_buffs)
  }
}
```

```
thread consumer {
  while(1){
    down(full_buffs)
    c = buf[OutP]
    OutP = OutP + 1 mod n
    up(empty_buffs)
    // Consume char...
  }
}
```

Producer consumer problem

- What is the shared state in the last solution?
- Does it apply mutual exclusion? If so, how?



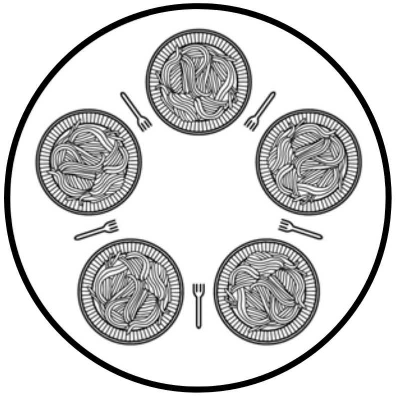
Producer and consumer are separate threads

Problems with solution

- **What if we have multiple producers and multiple consumers?**
  - Producer-specific and consumer-specific data becomes shared
  - We need to define and protect critical sections

Dining philosophers problem

- Five philosophers sit at a table
- One fork between each philosopher



Each philosopher is modeled with a thread

```
while(TRUE) {
  Think();
  Grab first fork;
  Grab second fork;
  Eat();
  Put down first fork;
  Put down second fork;
}
```

- *Why do they need to synchronize?*
- *How should they do it?*

Is this a valid solution?

```
#define N 5

Philosopher() {
  while(TRUE) {
    Think();
    take_fork(i);
    take_fork((i+1)% N);
    Eat();
    put_fork(i);
    put_fork((i+1)% N);
  }
}
```

Problems

- Potential for deadlock !

Working towards a solution …

```
#define N 5

Philosopher() {
  while(TRUE) {
    Think();
    take_fork(i);
    take_fork((i+1)% N);
    Eat();
    put_fork(i);
    put_fork((i+1)% N);
  }
}
```

take_forks(i)

put_forks(i)

Working towards a solution …

```
#define N 5

Philosopher() {
  while(TRUE) {
    Think();
    take_forks(i);
    Eat();
    put_forks(i);
  }
}
```

Picking up forks

```
int state[N]
semaphore mutex = 1
semaphore sem[i]
```

```
take_forks(int i) {
  wait(mutex);
  state [i] = HUNGRY;
  test(i);
  signal(mutex);
  wait(sem[i]);
}
```

```
// only called with mutex set!

test(int i) {
 if (state[i] == HUNGRY &&
     state[LEFT] != EATING &&
     state[RIGHT] != EATING){
   state[i] = EATING;
   signal(sem[i]);
 }
}
```

Putting down forks

```
int state[N]
semaphore mutex = 1
semaphore sem[i]
```

```
put_forks(int i) {
  wait(mutex);
  state [i] = THINKING;
  test(LEFT);
  test(RIGHT);
  signal(mutex);
}
```

```
// only called with mutex set!

test(int i) {
 if (state[i] == HUNGRY &&
     state[LEFT] != EATING &&
     state[RIGHT] != EATING){
   state[i] = EATING;
   signal(sem[i]);
 }
}
```

Dining philosophers

- Is the previous solution correct?
- What does it mean for it to be correct?
- Is there an easier way?

The sleeping barber problem

The sleeping barber problem

- ***Barber:***
  - While there are people waiting for a hair cut, put one in the barber chair, and cut their hair
  - When done, move to the next customer
  - Else go to sleep, until someone comes in

- ***Customer:***
  - If barber is asleep wake him up for a haircut
  - If someone is getting a haircut wait for the barber to become free by sitting in a chair
  - If all chairs are all full, leave the barbershop

Designing a solution

- **How will we model the barber and customers?**
- **What state variables do we need?**
  - .. and which ones are shared?
  - …. and how will we protect them?
- **How will the barber sleep?**
- **How will the barber wake up?**
- **How will customers wait?**
- **What problems do we need to look out for?**

Is this a good solution?

```
const CHAIRS = 5
var customers: Semaphore
    barbers: Semaphore
    lock: Mutex
    numWaiting: int = 0
```

Barber Thread:

```
  while true
    Wait(customers)
    Lock(lock)
    numWaiting = numWaiting-1
    Signal(barbers)
    Unlock(lock)
    CutHair()
  endWhile
```

Customer Thread:

```
  Lock(lock)
  if numWaiting < CHAIRS
    numWaiting = numWaiting+1
    Signal(customers)
    Unlock(lock)
    Wait(barbers)
    GetHaircut()
  else  -- give up & go home
    Unlock(lock)
  endIf
```

The readers and writers problem

- **Multiple readers and writers want to access a database (each one is a thread)**
- **Multiple readers can proceed concurrently**
- **Writers must synchronize with readers and other writers**
  - *only one writer at a time !*
  - *when someone is writing, there must be no readers !*

Goals:

- Maximize concurrency.
- Prevent starvation.

Designing a solution

- **How will we model the readers and writers?**
- **What state variables do we need?**
  - .. and which ones are shared?
  - …. and how will we protect them?
- **How will the writers wait?**
- **How will the writers wake up?**
- **How will readers wait?**
- **How will the readers wake up?**
- **What problems do we need to look out for?**

Is this a valid solution to readers & writers?

```
var mut: Mutex = unlocked
    db: Semaphore = 1
    rc: int = 0
```

Writer Thread:

```
  while true
    ...Remainder Section...
    Wait(db)
    ...Write shared data...
    Signal(db)
  endWhile
```

Reader Thread:

```
  while true
    Lock(mut)
    rc = rc + 1
    if rc == 1
      Wait(db)
    endIf
    Unlock(mut)
    ... Read shared data...
    Lock(mut)
    rc = rc - 1
    if rc == 0
      Signal(db)
    endIf
    Unlock(mut)
    ... Remainder Section...
  endWhile
```

Readers and writers solution

- **Does the previous solution have any problems?**
  - is it “fair”?
  - can any threads be starved? If so, how could this be fixed?
  - … and how much confidence would you have in your solution?

Quiz

- **What is a race condition?**
- **How can we protect against race conditions?**
- **Can locks be implemented simply by reading and writing to a binary variable in memory?**
- **How can a kernel make synchronization-related system calls atomic on a uniprocessor?**
  - Why wouldn't this work on a multiprocessor?
- **Why is it better to block rather than spin on a uniprocessor?**
- **Why is it sometimes better to spin rather than block on a multiprocessor?**

Quiz

- When faced with a concurrent programming problem, what strategy would you follow in designing a solution?
- What does all of this have to do with Operating Systems?