Concurrent Programming in Harmony: Signaling and Conditional Critical Sections

CS 4410
Operating Systems

[Robbert van Renesse]

Remember the recruiter…

Asked >100 candidates if they could implement two threads, where one thread had to wait for a signal from the other

none of them were able to do it without hints
only some of them were able to do it with hints

(as far as I know, none of them were Cornell grads ;-)

Can be done with busy-waiting

```
def T0():
    while not done:
        pass;
    ;
;
def T1():
    done = True;
;

done = False;
spawn T0();
spawn T1();
```

Can be done with busy-waiting

```
def T0():
    while not done:
        pass;
    ;
;
def T1():
    done = True;
;

done = False;
spawn T0();
spawn T1();
```

we don't like busy waiting

Can be done with busy-waiting

```
def T0():
    await done;
;
def T1():
    done = True;
;

done = False;
spawn T0();
spawn T1();
```

we don’t like busy waiting

Can be done with locks, awkwardly

```
import synch;

def T0():
        lock(?condition);
        assert done;    # make sure T1 sent signal
        # no unlock
;
def T1():
        # no lock
        done = True;
        unlock(?condition);
;

done = False;
condition = Lock();
lock(?condition);    # weird stuff during init…
spawn T0();
spawn T1();
```

Can be done with locks, awkwardly

```
import synch;

def T0():
        lock(?condition);
        assert done;    # make sure T1 sent signal
        # no unlock
;
def T1():
        # no lock
        done = True;
        unlock(?condition)
;

done = False;
condition = Lock();
lock(?condition);     #                              t…
spawn T0();
spawn T1();
```

locks should be nested

Enter (*binary*) *semaphores*

[Dijkstra 1962]

Binary Semaphore

- Two-valued counter: 0 or 1
- Two operations:
  - P(rocure)
    - waits until counter is 1, then sets the counter to 0. Akin to decrementing
  - V(acate)
    - can only be called legally if the counter is 0. Sets the counter to 1. Akin to incrementing
- No operation to read the value of the counter!

Difference with locks

Locks	**(Binary) Semaphores**
Initially "unlocked"	Can be initialized to 0 or 1
Usually locked, then unlocked by same process (although see R/W lock)	Can be *procured* and *vacated* by different processes
Either held or not	Can be easily generalized to *counting semaphores*
Mostly used to implement critical sections	Can be used to implement critical sections as well as waiting for special conditions

but both are much like "*batons*" that are being passed

Counting Semaphores?

- Book starts with counting semaphores
- We will start concentrate on binary semaphores…

Binary Semaphore interface and implementation

```
def Semaphore(cnt):
    result = cnt;
;
def P(sema):
    let blocked = True:
        while blocked:
            atomic:
                if (!sema) > 0:
                    !sema -= 1;
                    blocked = False;
                ;
            ;
        ;
    ;
;
def V(sema):
    atomic:
        !sema += 1;
    ;
;
```

sema = Semaphore(0 or 1)

P(?*sema*) “procures” *sema*

This means that it tries to decrement the semaphore, blocking if it is 0.

V(?*sema*) “vacates” *sema*

This means incrementing the semaphore.

Same example with semaphores

```
import synch;

def T0():
    P(?condition);    # wait for signal
    assert done;
;
def T1():
    done = True;
    V(?condition);    # send signal
;

done = False;
condition = Semaphore(0);
spawn T0();
spawn T1();
```

Semaphores can be locks too

- *lk* = Semaphore(1) # 1-initialized
- P(?*lk*) # lock
- V(?*lk*) # unlock

Great, what else can one do with binary semaphores??

Conditional Critical Sections

- A critical section with a condition
- For example:
  - dequeue(), but wait until the queue is non-empty
    - don't want two threads to run dequeue code at the same time, but also don't want any thread to run dequeue code when queue is empty
  - print(), but wait until the printer is idle
  - acquire_rlock(), but only if there are no writers in the critical section
  - allocate 100 GPUs, when they become available
  - …

[Hoare 1973]

Multiple conditions

Some conditional critical sections can have multiple conditions:

- R/W lock: readers are waiting for writer to leave; writers are waiting for reader or writer to leave
- bounded queue: dequeuers are waiting for queue to be non-empty; enqueuers are waiting for queue to be non-full
- …

High-level idea: selective baton passing!

- When a process wants to execute in the critical section, it needs the one baton
- Processes can be waiting for different conditions
  - such processes do not hold the baton
- When a process with the baton leaves the critical section, it checks to see if there are processes waiting on a condition that now holds
- If so, it passes the baton to one such process
- If not, the critical section is vacated and the baton is free to pick up for another process that comes along

“Split Binary Semaphores” [Hoare 1973]

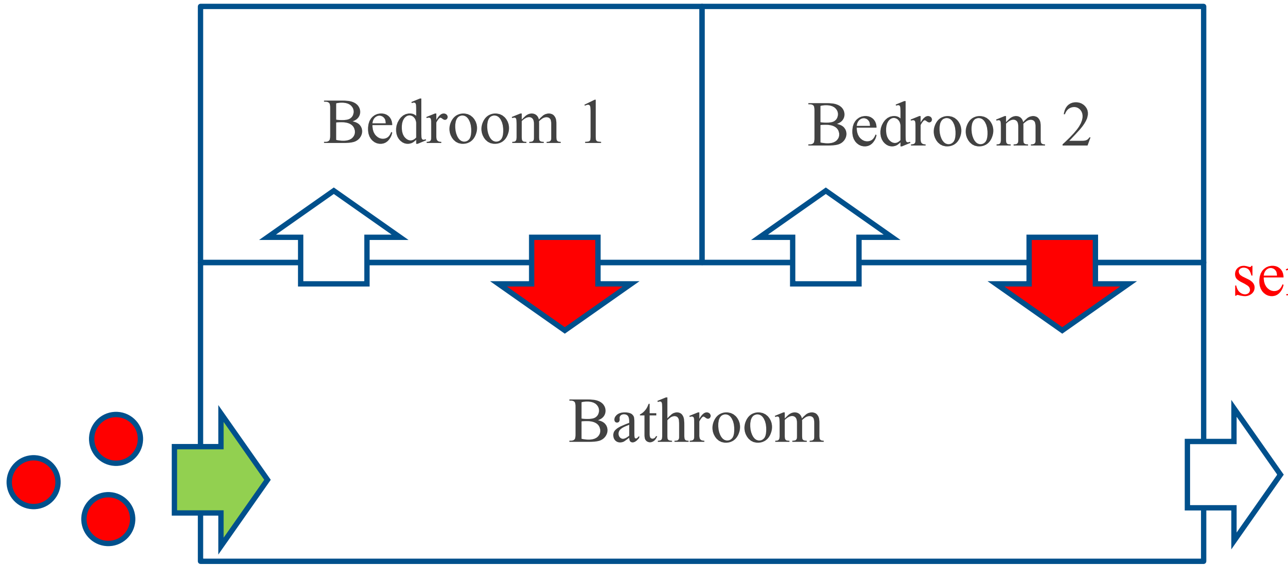
- Implement baton passing with multiple binary semaphores
- If there are *N* conditions, you’ll need *N*+1 binary semaphores
  - one for each condition
  - one to enter the critical section in the first place
- At most one of these semaphores has value 1
  - If all are 0, baton held by some process
  - If one semaphore is 1, no process holds the baton
    - if it’s the “entry” semaphore, then no process is waiting on a condition that holds, and any process can enter
    - if it’s one of the condition semaphores, some process that is waiting on the condition can now enter the critical section

Bathroom humor…

holds baton

does not hold baton

3 processes want to enter critical section



semaphore = 0

semaphore = 1

Bathroom: critical section
Bedrooms: waiting conditions

at any time exactly one semaphore or process is green (and thus at most one semaphore is green)

This is a model of:

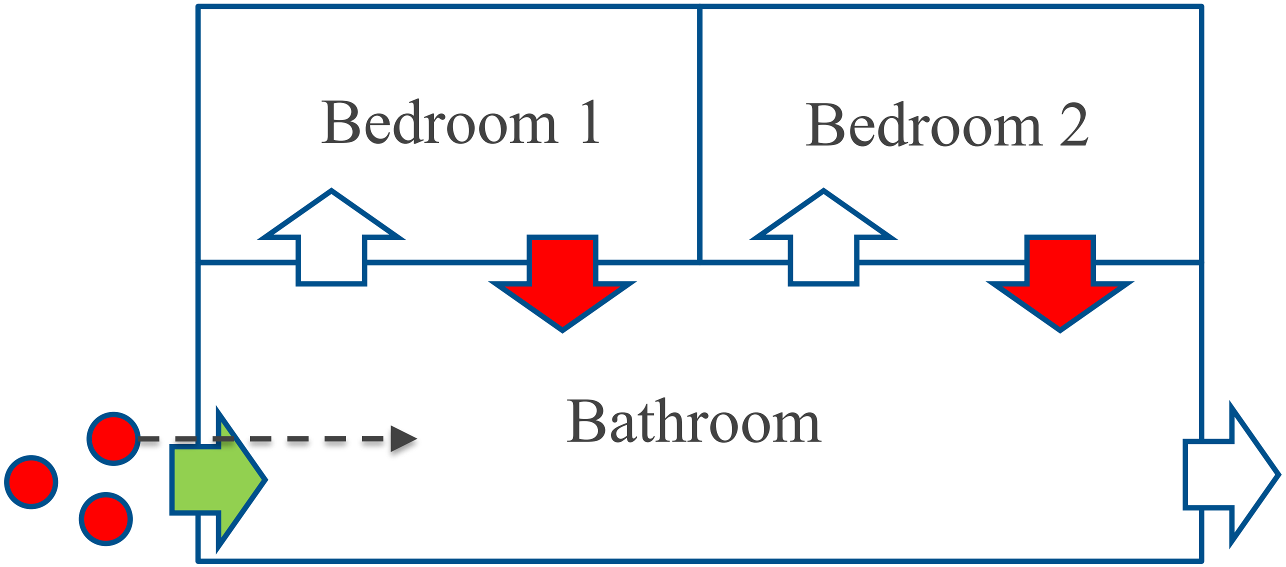
- Reader/writer lock:
  - Bathroom: critical section
  - Bedroom 1: readers waiting for writer to leave
  - Bedroom 2: writers waiting for readers or writers to leave
- Bounded queue:
  - Bathroom: critical section
  - Bedroom 1: dequeuers waiting for queue to be non-empty
  - Bedroom 2: enqueuers waiting for queue to be non-full
- …

Bathroom humor…

holds baton

does not hold baton

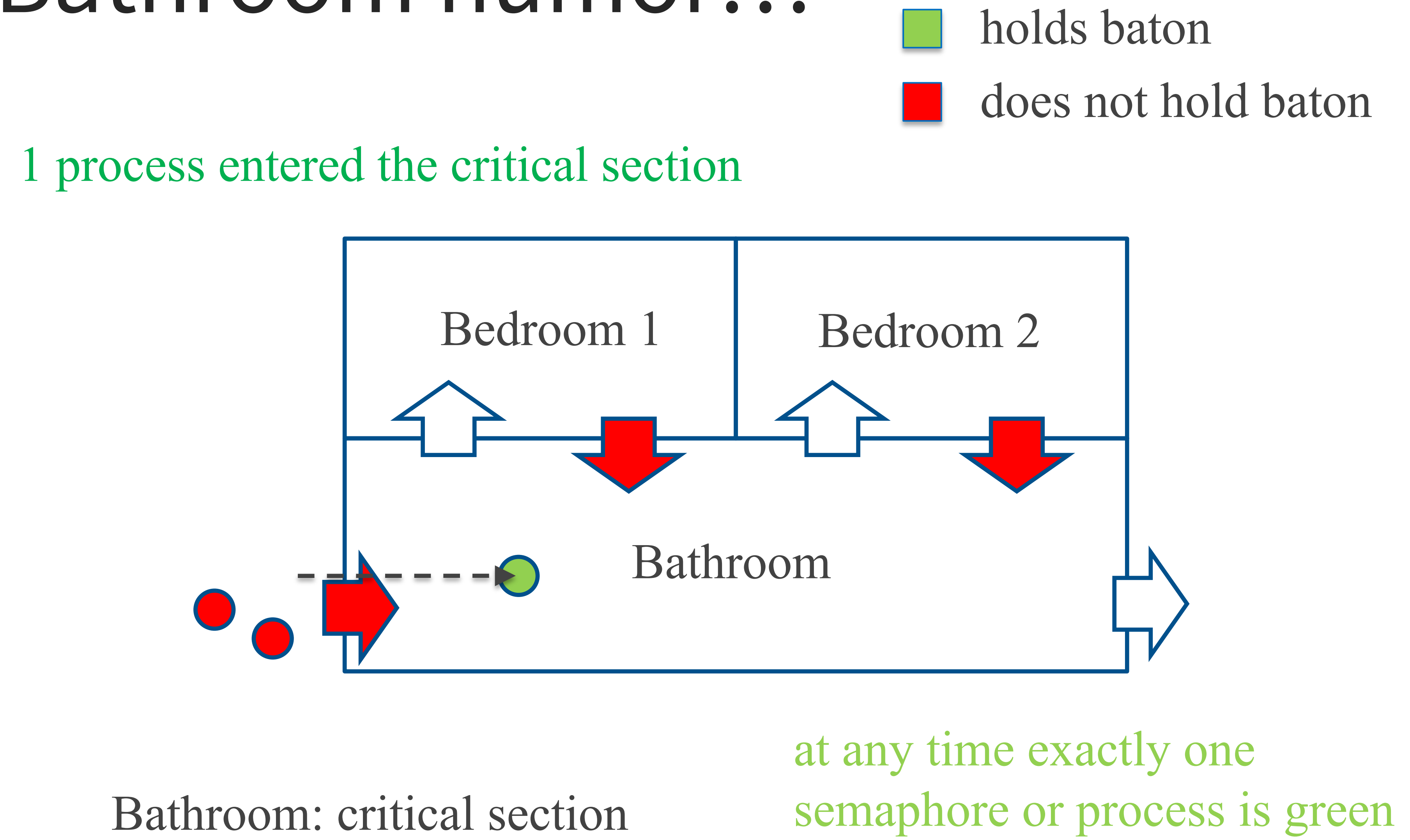
3 processes want to enter critical section



Bathroom: critical section
Bedrooms: waiting conditions

at any time exactly one semaphore or process is green

Bathroom humor…



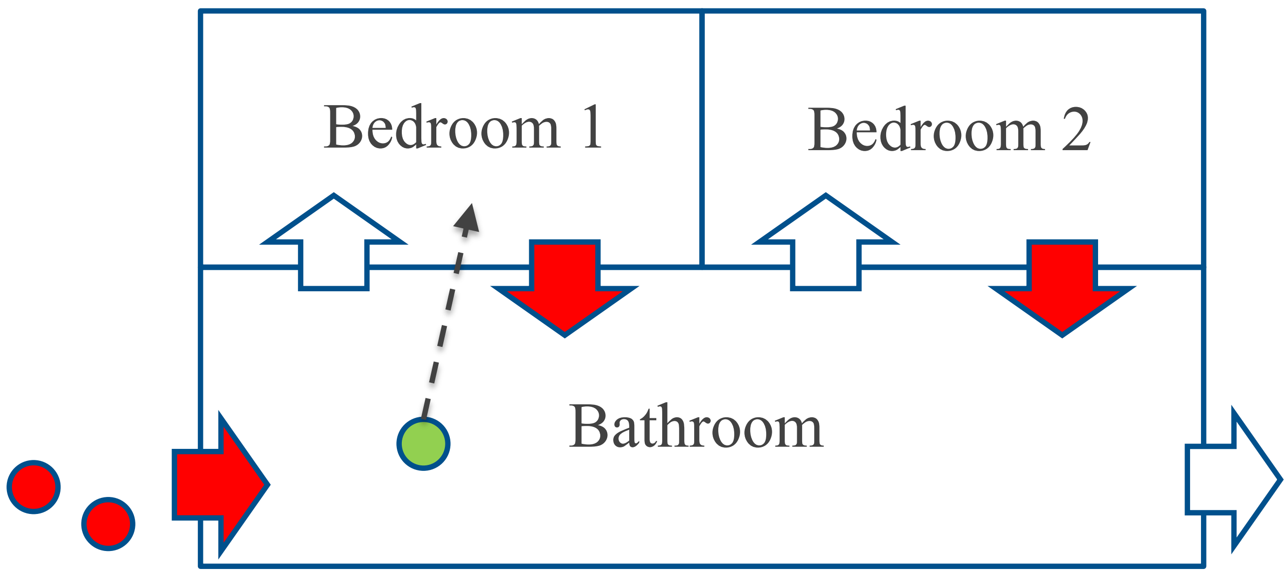
Bathroom: critical section
Bedrooms: waiting conditions

Bathroom humor…

holds baton

does not hold baton

process needs to wait for Condition 1



Bathroom: critical section
Bedrooms: waiting conditions

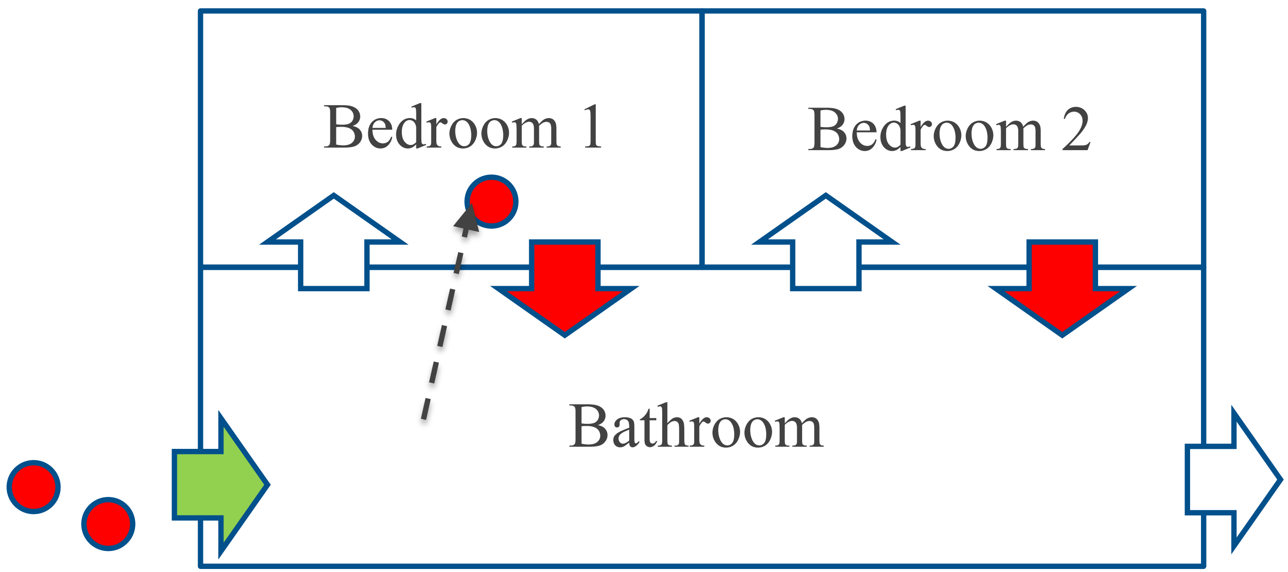
at any time exactly one semaphore or process is green

Bathroom humor…

holds baton

does not hold baton

no process waiting for condition that holds



Bathroom: critical section
Bedrooms: waiting conditions

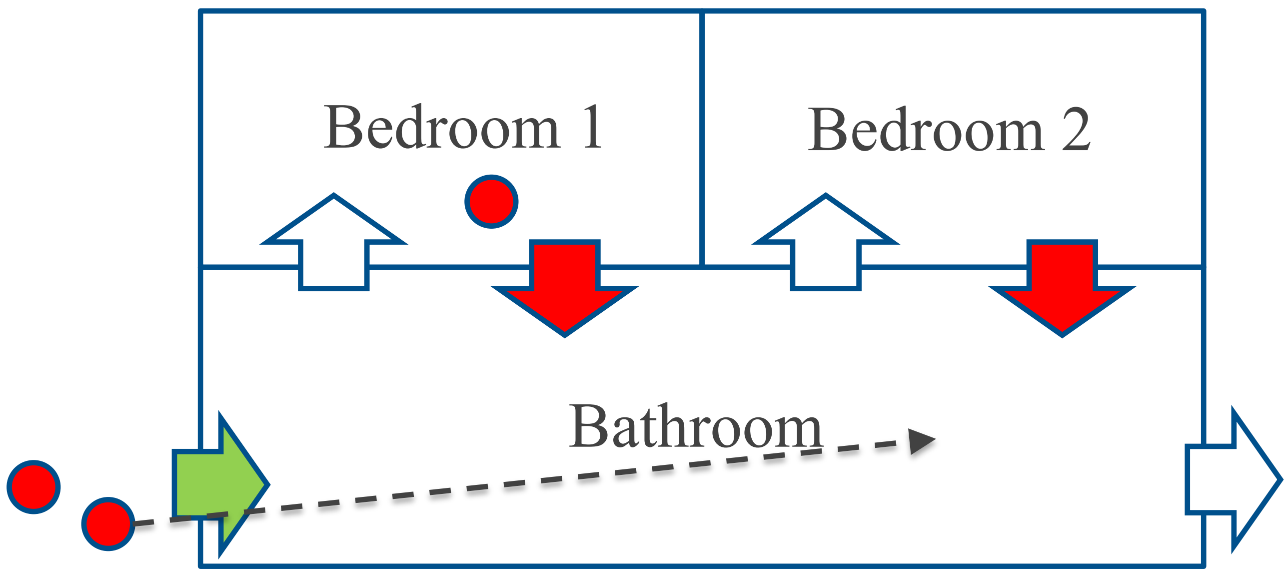
at any time exactly one
semaphore or process is green

Bathroom humor…

holds baton (green)

does not hold baton (red)

another process can enter the critical section



Bathroom: critical section

Bedrooms: waiting conditions

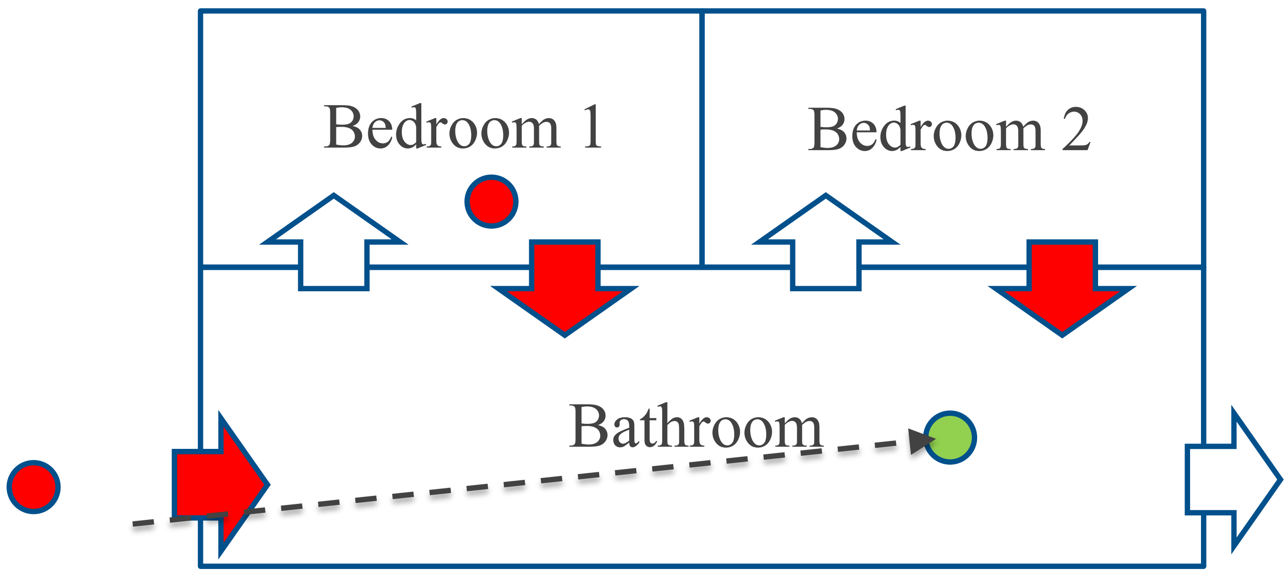
at any time exactly one semaphore or process is green

Bathroom humor…

holds baton

does not hold baton

process entered the critical section



at any time exactly one semaphore or process is green

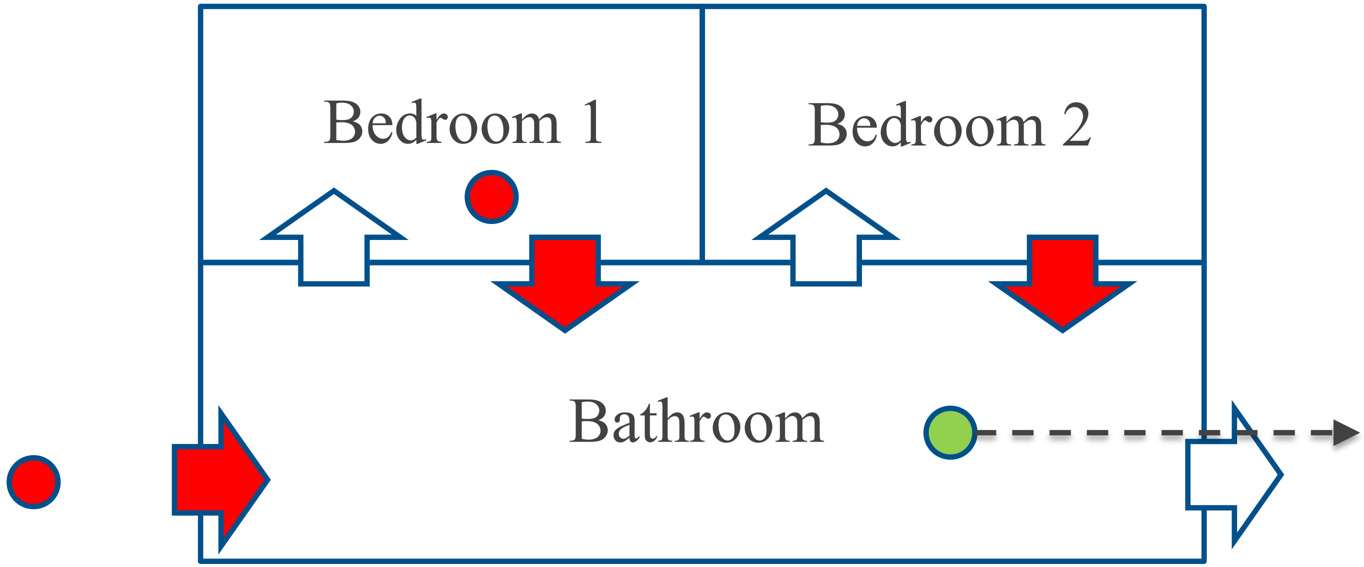
Bathroom: critical section
Bedrooms: waiting conditions

Bathroom humor…

holds baton

does not hold baton

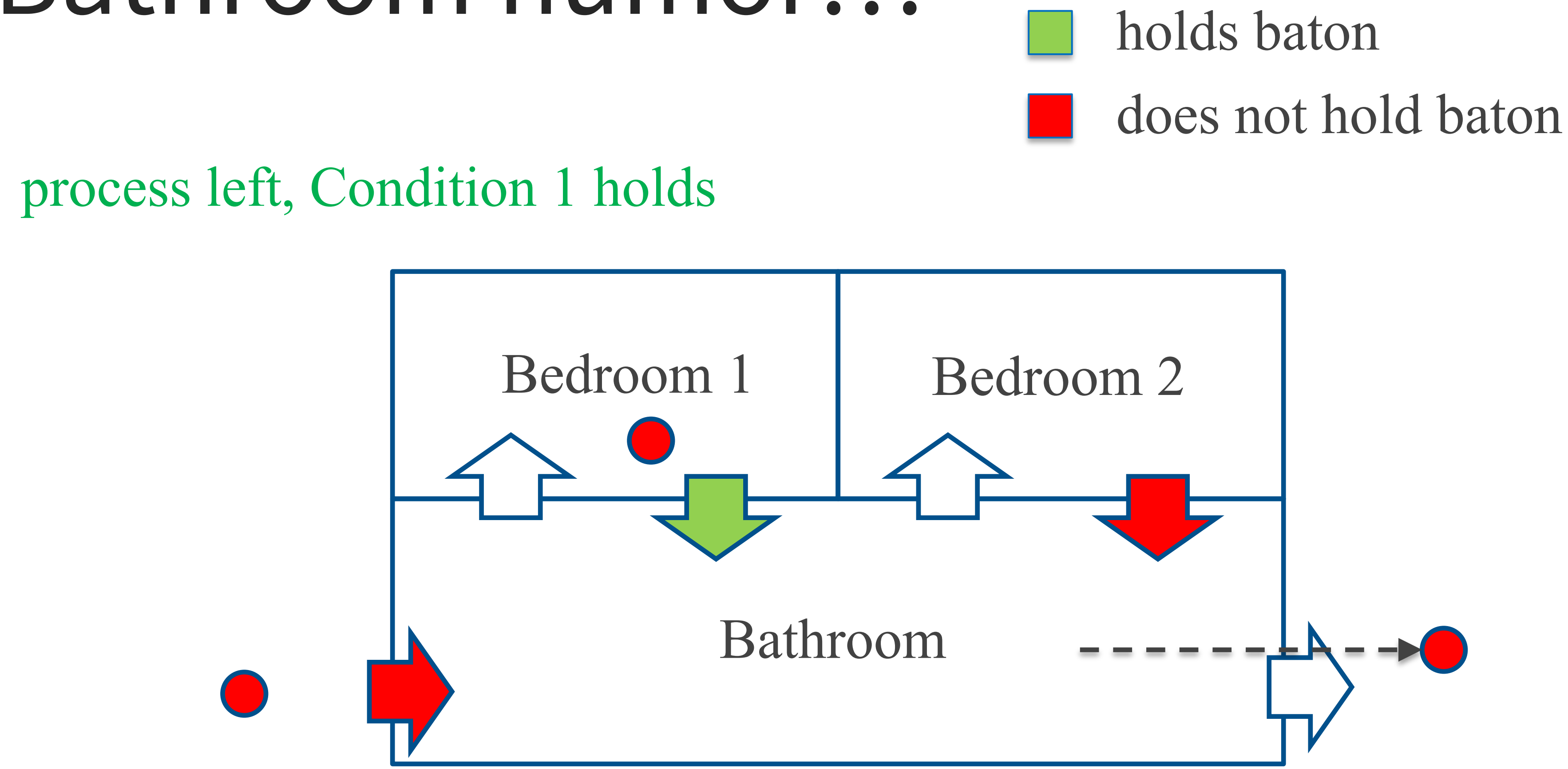
process enables Condition 1 and wants to leave



Bathroom: critical section
Bedrooms: waiting conditions

at any time exactly one semaphore or process is green

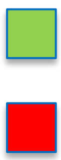
Bathroom humor…



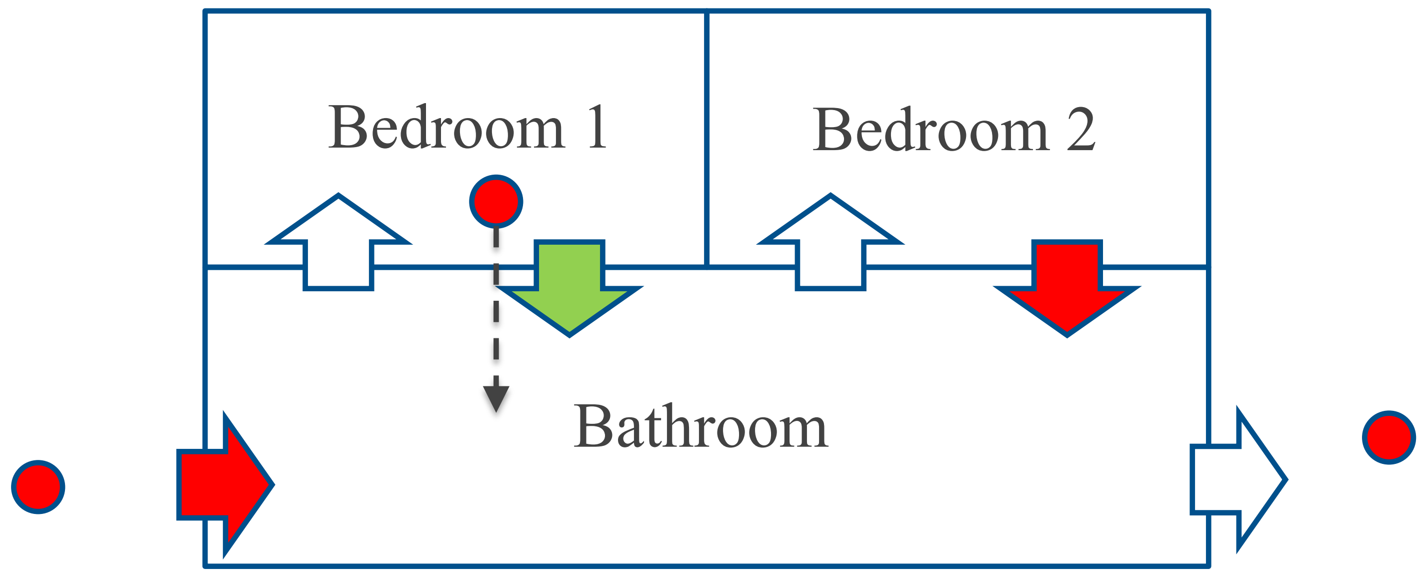
at any time exactly one semaphore or process is green

Bathroom: critical section
Bedrooms: waiting conditions

Bathroom humor…



first process (and only first process) can enter critical section again

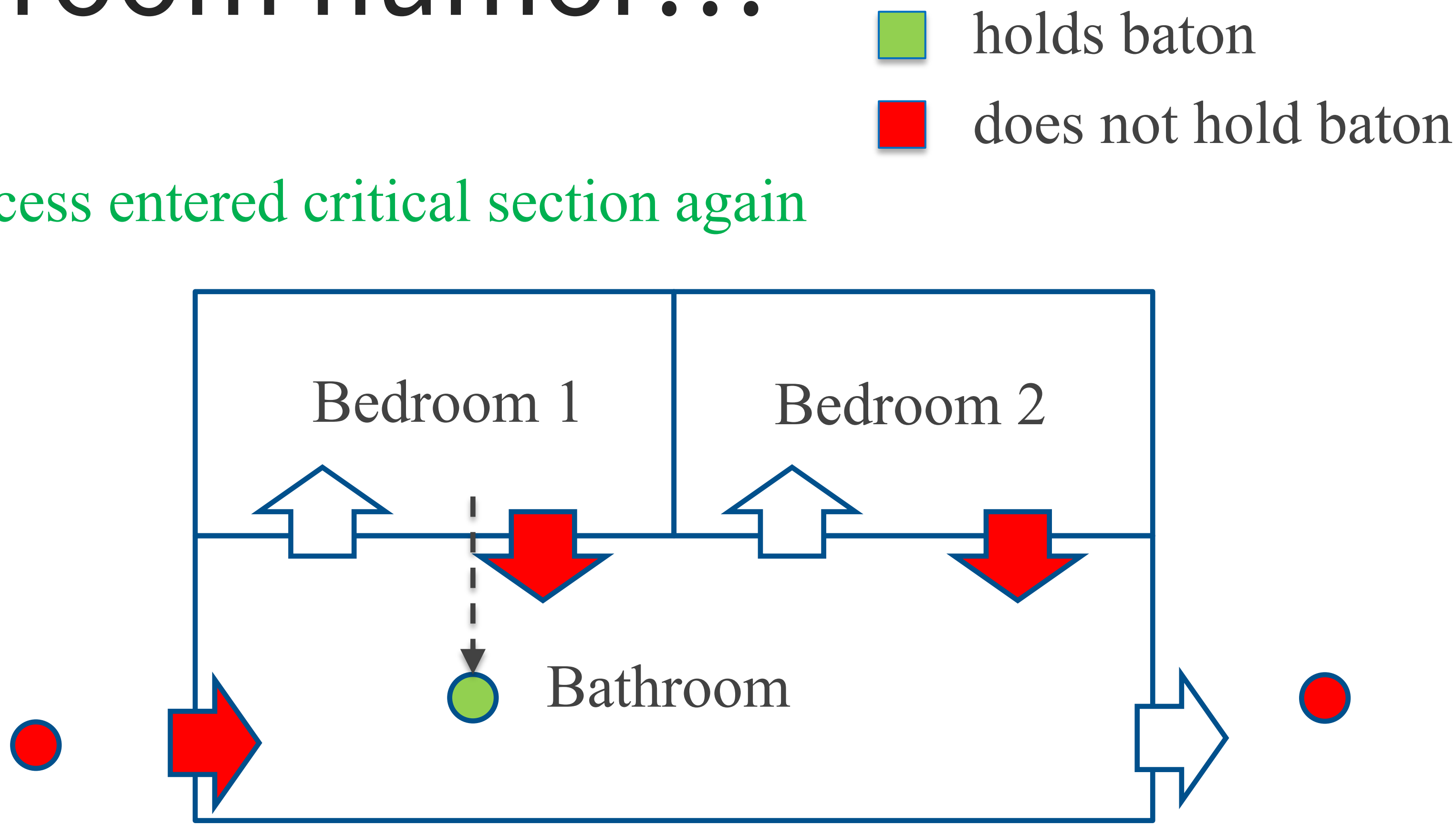


Bathroom: critical section
Bedrooms: waiting conditions

at any time exactly one semaphore or process is green

Bathroom humor…

first process entered critical section again



Bathroom: critical section
Bedrooms: waiting conditions

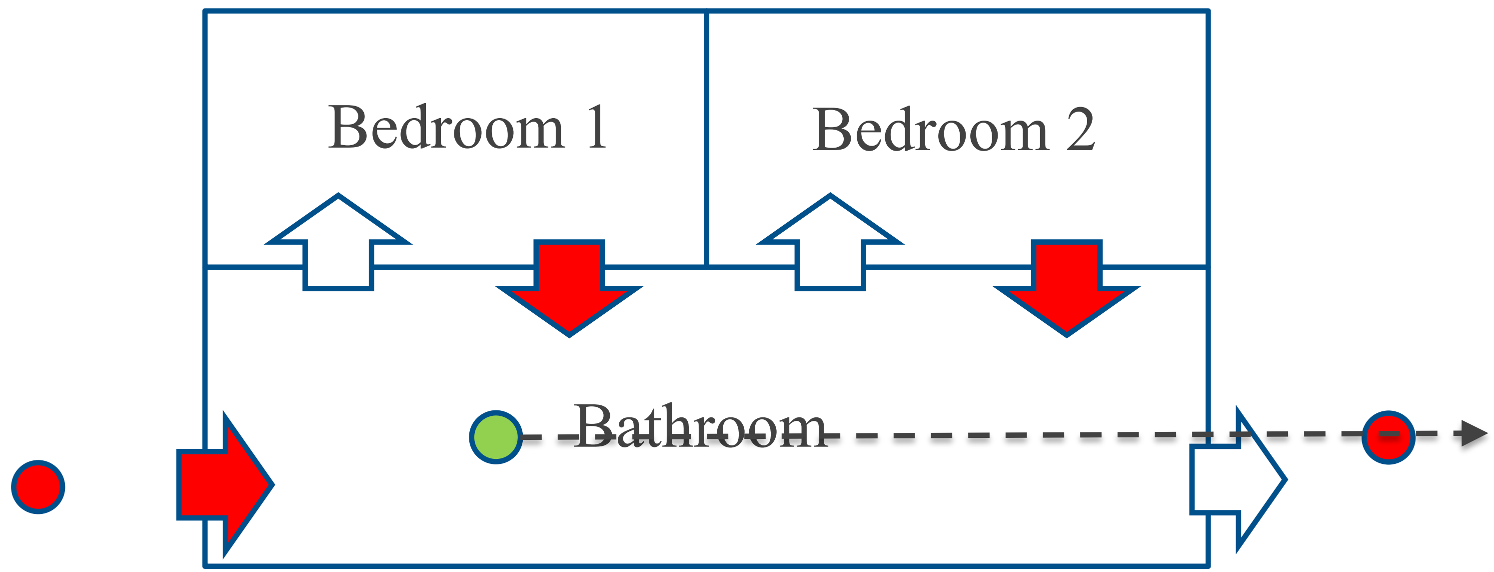
at any time exactly one semaphore or process is green

Bathroom humor…

holds baton

does not hold baton

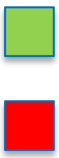
First process leaves without either condition holding



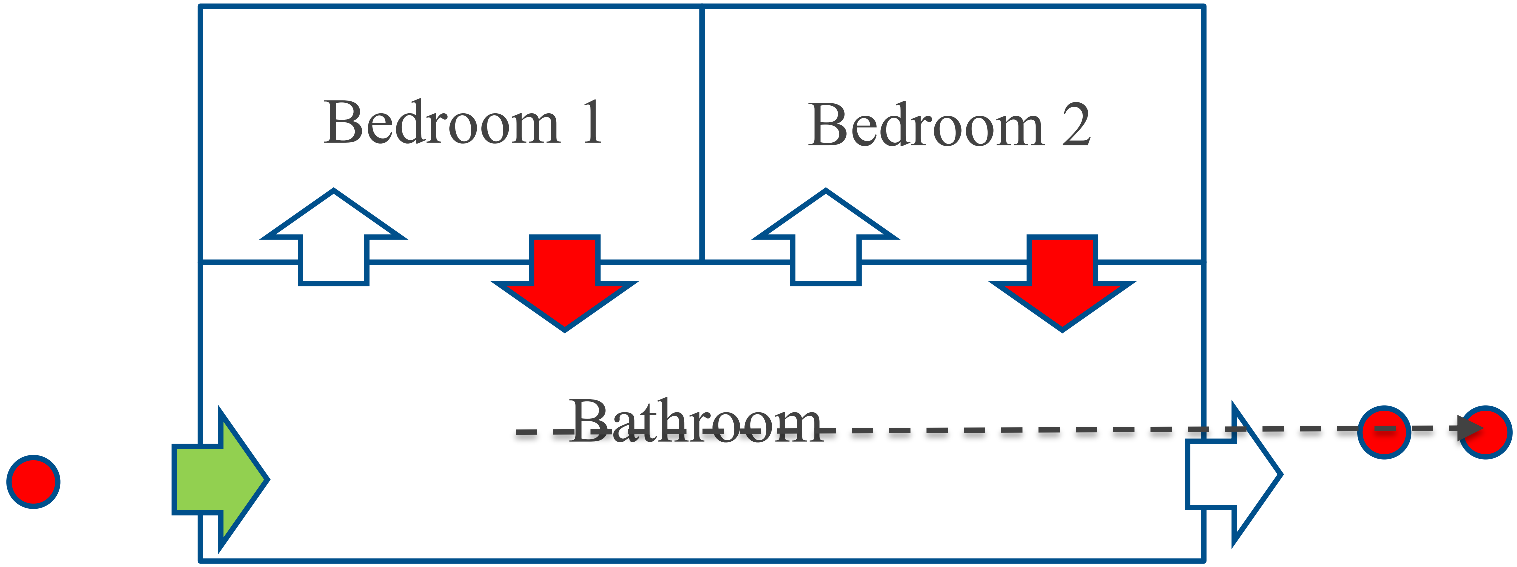
at any time exactly one semaphore or process is green

Bathroom: critical section
Bedrooms: waiting conditions

Bathroom humor…



First process done



at any time exactly one semaphore or process is green

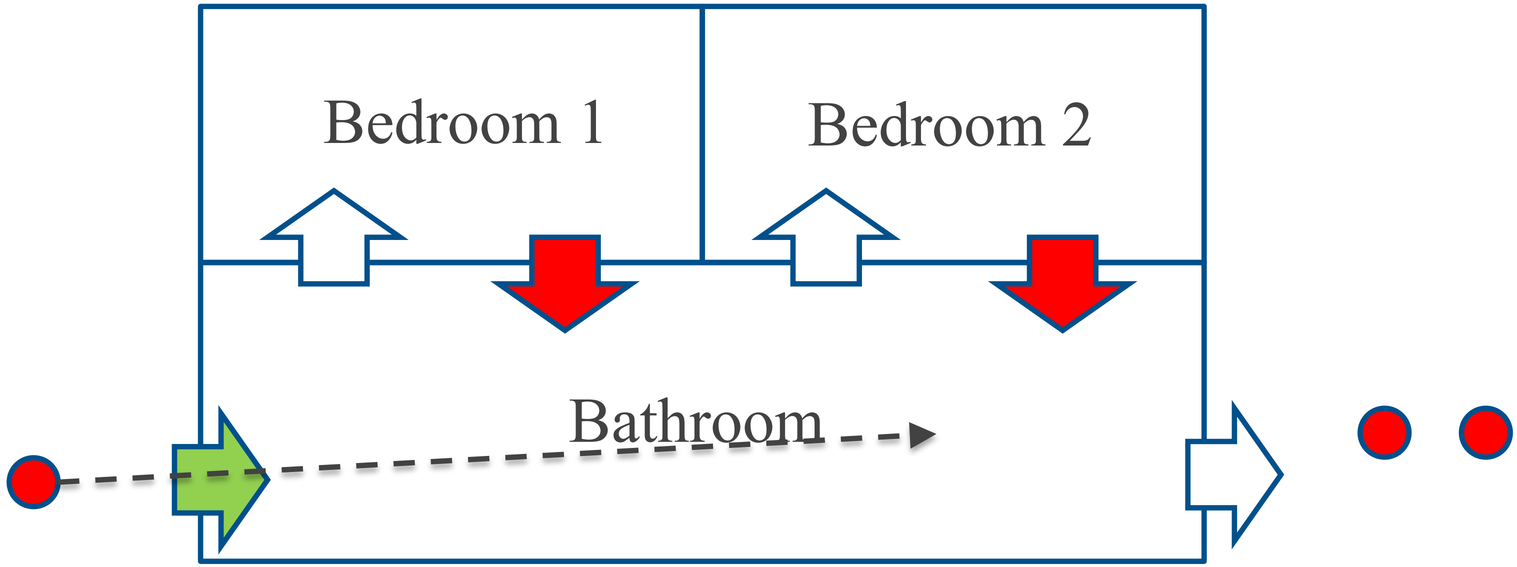
Bathroom: critical section
Bedrooms: waiting conditions

Bathroom humor…

holds baton

does not hold baton

One process want to enter the critical section



Bathroom: critical section
Bedrooms: waiting conditions

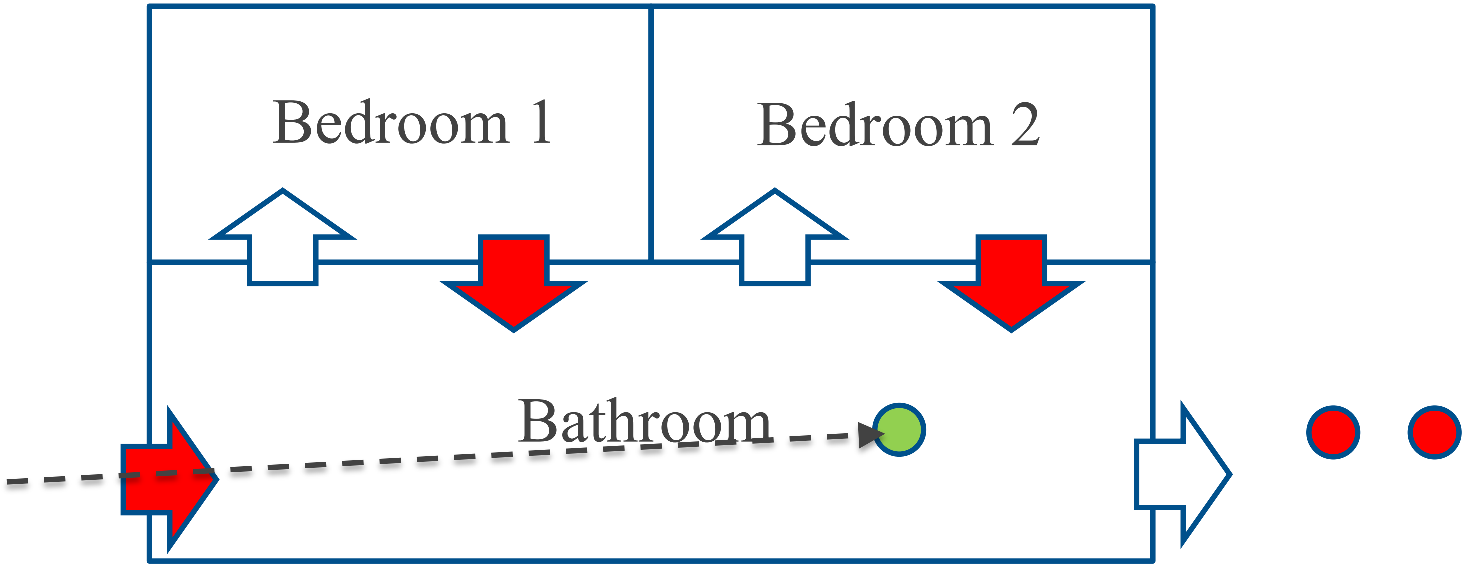
at any time exactly one semaphore or process is green

Bathroom humor…

■ holds baton

■ does not hold baton

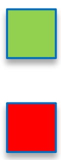
Last process entered critical section



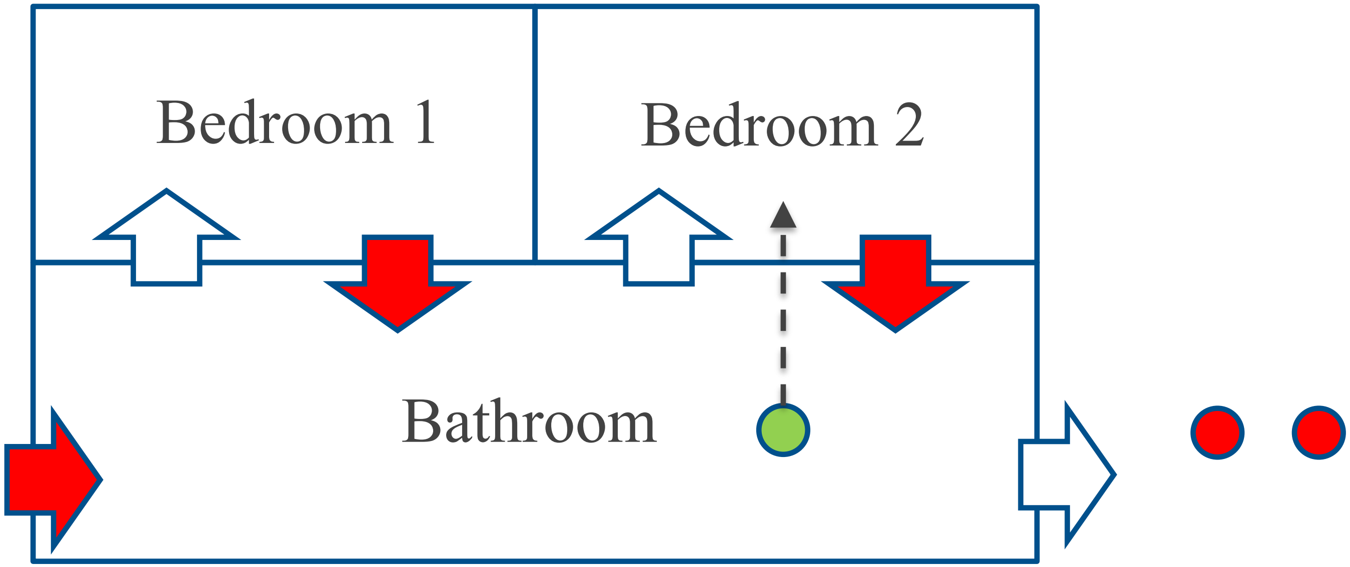
Bathroom: critical section
Bedrooms: waiting conditions

at any time exactly one semaphore or process is green

Bathroom humor…



Process needs to wait for Condition 2

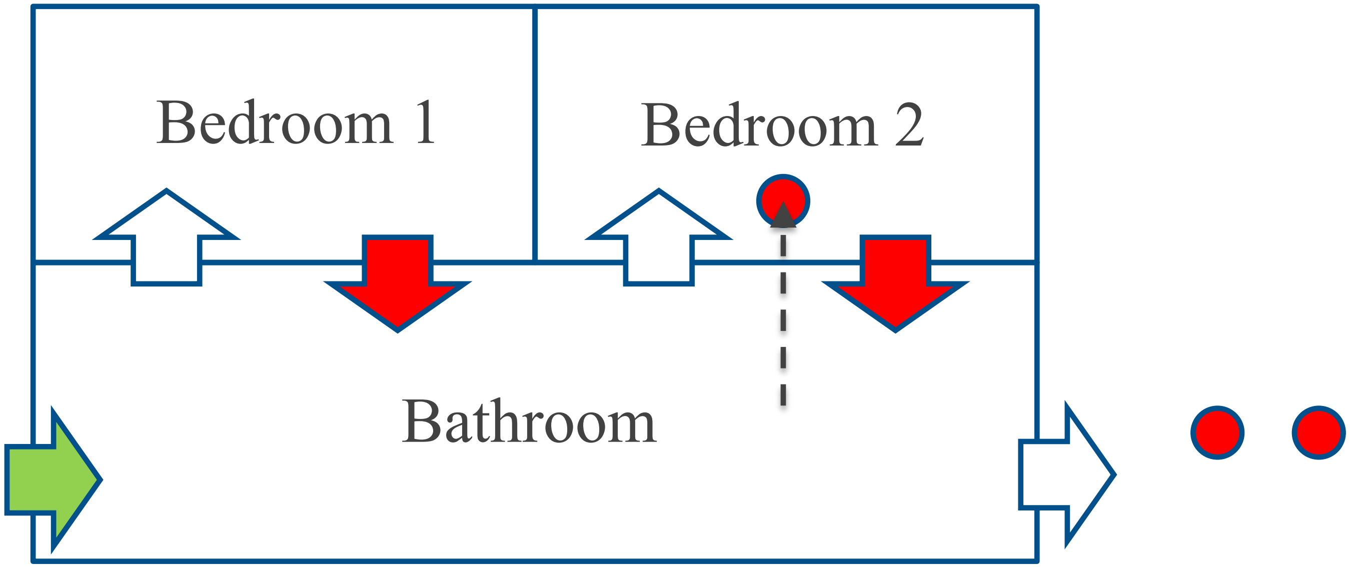


at any time exactly one semaphore or process is green

Bathroom: critical section
Bedrooms: waiting conditions

Bathroom humor…

Process waiting for Condition 2



at any time exactly one semaphore or process is green

Bathroom: critical section
Bedrooms: waiting conditions

Reader/writer lock, again

```
mutex, r_sema, w_sema = Semaphore(1), Semaphore(0), Semaphore(0);
r_entered, r_waiting, w_entered, w_waiting = 0, 0, 0, 0;
```

Figure 15.1: [code/RWsbs.hny] Reader/Writer Lock using Split Binary Semaphores.

Accounting:

- *r_entered*: #readers in the critical section
- *r_waiting*: #readers waiting to enter the critical section
- *w_entered*: #writers in the critical section
- *w_waiting*: #writers waiting to enter the critical section

Invariants:

- if n readers in the critical section, then $nreaders \geq n$
- if n writers in the critical section, then $nwriters \geq n$
- $(nreaders \geq 0 \land nwriters = 0) \lor (nreaders = 0 \land 0 \leq nwriters \leq 1)$

Reader/writer lock, again

```
def acquire_rlock():
    P(?mutex);
    if w_entered > 0:
        r_waiting += 1;
        V(?mutex); P(?r_sema);
        r_waiting −= 1;
    ;
    r_entered += 1;
    V_one();
;
def release_rlock():
    P(?mutex);
    r_entered −= 1;
    V_one();
;
```

Reader/writer lock, again

```
def acquire_rlock():
    P(?mutex);
    if w_entered > 0:
        r_waiting += 1;
        V(?mutex); P(?r_sema);
        r_waiting -= 1;
    ;
    r_entered += 1;
    V_one();
;
def release_rlock():
    P(?mutex);
    r_entered -= 1;
    V_one();
;
```

enter bedroom 1

leave critical section

Reader/writer lock, again

```
def acquire_wlock():
    P(?mutex);
    if (r_entered + w_entered) > 0:
        w_waiting += 1;
        V(?mutex); P(?w_sema);
        w_waiting −= 1;
    ;
    w_entered += 1;
    V_one();
;
def release_wlock():
    P(?mutex);
    w_entered −= 1;
    V_one();
;
```

Reader/writer lock, again

```
def acquire_wlock():
    P(?mutex);
    if (r_entered + w_entered) > 0:
        w_waiting += 1;
        V(?mutex); P(?w_sema);
        w_waiting −= 1;
    ;
    w_entered += 1;
    V_one();
;
def release_wlock():
    P(?mutex);
    w_entered −= 1;
    V_one();
;
```

enter bedroom 2

leave critical section

Reader/writer lock, again

```
import synch;

def V_one():
    if (w_entered == 0) and (r_waiting > 0): V(?r_sema);
    elif ((r_entered + w_entered) == 0) and (w_waiting > 0): V(?w_sema);
    else: V(?mutex);
    ;
;
```

When leaving critical section:

- if no writers in the Critical Section and there are readers waiting

  then let a reader in
- else if no readers nor writer in the C.S. and there are writers waiting

  then let a writer in
- otherwise

  let any new process in

Reader/writer lock, again

```
import synch;

def V_one():
    if (w_entered == 0) and (r_waiting > 0): V(?r_sema);
    elif ((r_entered + w_entered) == 0) and (w_waiting > 0): V(?w_sema);
    else: V(?mutex);
    ;
;
```

When leaving critical section:

- if no writers in the Critical Section and there are readers waiting
  then let a reader in
- else if no readers nor writer in the C.S. and there are writers waiting
  then let a writer in
- otherwise
  let any new process in

- Can the two conditions be reversed?
- What is the effect of that?

Split Binary Semaphore rules

- *N*+1 binary semaphores
  - 1 ”entry” semaphore and *N* condition semaphores
- Initially only the “entry” semaphore is 1
- Sum of semaphores should always be 0 or 1

➔ each process should start with a P operation, alternate V and P operations, and end on a V operation

➔ never two Ps or two Vs in a row!!!!

- Keep careful track of state in shared variables
  - including one #waiting counter per condition
- Only access variables when sum of semaphores is 0

This “recipe” works for any synchronization problem where the number of conditions is fixed

Making R/W lock starvation-free

- Last implementation suffers from starvation

Making R/W lock starvation-free

- Solution 1: change the waiting and release conditions:
  - when a reader tries to enter the critical section, wait if there is a writer in the critical section OR if there are writers waiting to enter the critical section
  - exiting reader prioritizes releasing a waiting writer
  - exiting writer prioritizes releasing a waiting reader

See Figure 16.1

Making R/W lock starvation-free

- Solution 2: maintain a FCFS queue of all processes trying to enter
  - use a semaphore per process rather than per condition
    - (i.e., each process has its own condition)
  - the queue contains the semaphores that the processes in the queue are waiting for
  - processes at head of queue are awakened when possible (in a baton-passing style)
  - Works with a variable #conditions too!!!

See Figure 16.2

Conditional Critical Sections

We now know two ways to implement them:

Busy Waiting	Split Binary Semaphores
Wait for condition in loop, acquiring lock before testing condition and releasing it if the condition does not hold	Use a collection of binary semaphores and keep track of state including information about waiting processes
Easy to understand the code	State tracking is complicated
Ok for true multi-core, but bad for virtual threads	Good for both multi-core and virtual threading

Language support?

- Can’t the programming language be more helpful here?
  - Helpful syntax
  - Or at least some library support

“Hoare” Monitors

- Tony Hoare 1974
  - similar construct given by Per Brinch-Hansen 1973
- Syntactic sugar around split binary semaphores

```
single resource:monitor
begin busy:Boolean;
      nonbusy:condition;
   procedure acquire;
      begin if busy then nonbusy.wait;
                 busy := true
      end;
   procedure release;
      begin busy := false;
                nonbusy.signal
      end;
   busy := false; comment initial value;
end single resource
```

“condition variable”

wait method

signal method

“Hoare” Monitors

- Tony Hoare 1974
  - similar construct given by Per Brinch-Hansen 1973
- Syntactic sugar around split binary semaphores

```
single resource:monitor
begin busy:Boolean;
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   procedure acquire;
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               busy := true
      end;
   procedure release;
      begin busy := false;
            nonbusy.signal
      end;
   busy := false; comment initial value;
end single resource
```

```
def acquire():
    mon_enter();
        if busy:
            wait(?nonbusy);
        ;
        busy = True;
    mon_exit();
;
def release():
    mon_enter();
        busy = False;
        signal(?nonbusy);
    mon_exit();
;
mutex = Semaphore(1);
nonbusy = Condition(?mutex);
busy = False;
```

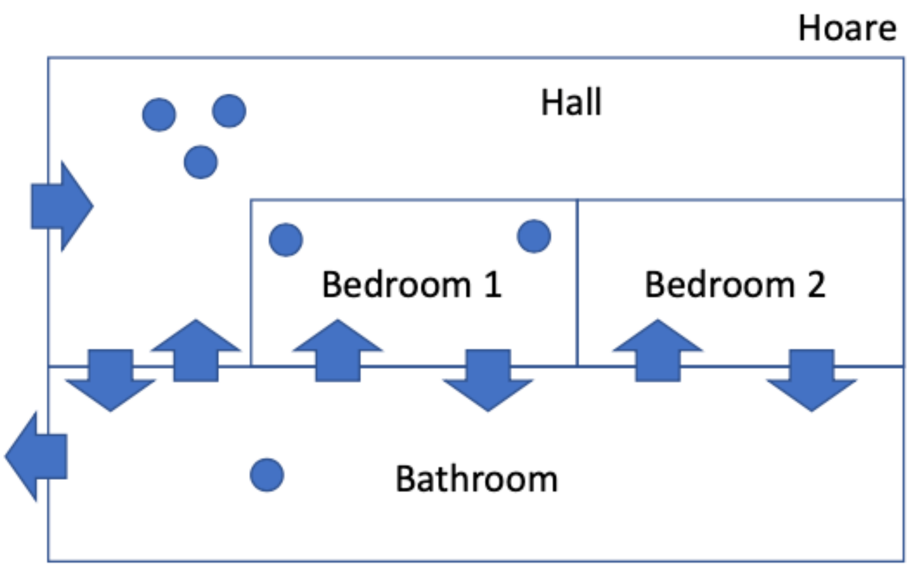
Hoare Monitors in Harmony

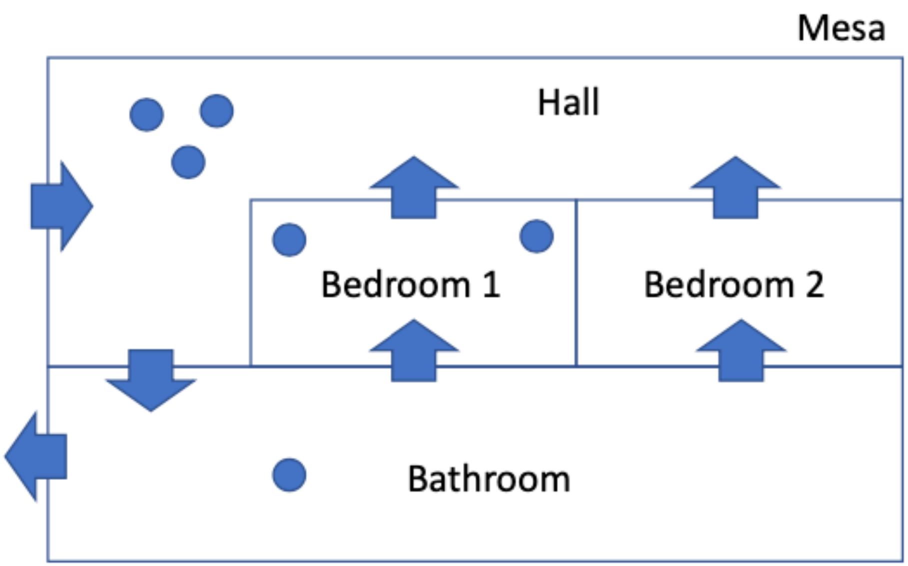
```
import synch;

def mon_enter():
    P(?mutex);
;
def mon_exit():
    V(?mutex);
;
def Condition(mon):
    result = dict{ .lock: mon, .sema: Semaphore(0), .count: 0 };
;
def wait(cond):
    cond→count += 1;
    V(cond→lock); P(?cond→sema);
    cond→count −= 1;
;
def signal(cond):
    if cond→count > 0:
        V(?cond→sema); P(cond→lock);
    ;
;
```

Mesa Monitors

- Introduced in the Mesa language
  - Xerox PARC, 1980
- Syntactically similar to Hoare monitors
- Semantically closer to busy waiting approach

Hoare vs Mesa Monitors





Hoare monitors	Mesa monitors
Baton passing approach	Sleep + try again
signal passes baton	notify(all) wakes sleepers

Mesa monitors won the test of time…

Mesa Monitors in Harmony

```
def Condition(lk):
    result = dict{ .lock: lk, .waiters: [] };
;
def wait(c):
    atomic:
        unlock(c->lock);
        stop c->waiters;
    ;
;
def notify(c):
    atomic:
        let lk, waiters = c->lock, c->waiters:
            if waiters != []:
                lk->suspended += [waiters[0],];
                c->waiters = tail(waiters);
            ;
        ;
    ;
;
def notifyAll(c):
    atomic:
        let lk, waiters = c->lock, c->waiters:
            lk->suspended += waiters;
            c->waiters = [];
        ;
    ;
```

mon_enter: grab lock

mon_exit: release lock

Condition: consists of lock + list of processes waiting

wait: unlock + add process context to list of waiters

notify: move one waiter to the list of suspended processes associated with the lock

notifyAll: move all waiters to the list of suspended processes associated with the lock

R/W lock with Mesa monitors

```
rwlock = Lock();
rcond, wcond = Condition(?rwlock), Condition(?rwlock);
nreaders, nwriters = 0, 0;
```

Figure 17.5: [code/RWcv.hny] Reader/Writer Lock using Mesa-style condition variables.

Invariants:

- if n readers in the critical section, then $nreaders \geq n$
- if n writers in the critical section, then $nwriters \geq n$
- $(nreaders \geq 0 \wedge nwriters = 0) \vee (nreaders = 0 \wedge 0 \leq nwriters \leq 1)$

rwlock protects the *nreaders*/*nwriters* variables, not the critical section!

R/W Lock, reader part

busy waiting

```
def acquire_rlock():
    lock(?rwlock);
    while nwriters > 0:
        unlock(?rwlock);
        lock(?rwlock);
    ;
    nreaders += 1;
    unlock(?rwlock);
;
def release_rlock():
    lock(?rwlock);
    nreaders −= 1;
    unlock(?rwlock);
;
```

Mesa monitor

```
def acquire_rlock():
    lock(?rwlock);
    while nwriters > 0:
        wait(?rcond);
    ;
    nreaders += 1;
    unlock(?rwlock);
;
def release_rlock():
    lock(?rwlock);
    nreaders −= 1;
    if nreaders == 0:
        notify(?wcond);
    ;
    unlock(?rwlock);
;
```

R/W Lock, reader part

busy waiting

```
def acquire_rlock():
    lock(?rwlock);
    while nwriters > 0:
        unlock(?rwlock);
        lock(?rwlock);
    ;
    nreaders += 1;
    unlock(?rwlock);
;
def release_rlock():
    lock(?rwlock);
    nreaders -= 1;
    unlock(?rwlock);
;
```

Mesa monitor

```
def acquire_rlock():
    lock(?rwlock);
    while nwriters > 0:
        wait(?rcond);
    ;
    nreaders += 1;
    unlock(?rwlock);
;
def release_rlock():
    lock(?rwlock);
    nreaders -= 1;
    if nreaders == 0:
        notify(?wcond);
    ;
    unlock(?rwlock);
;
```

R/W lock, writer part

busy waiting

```
def acquire_wlock():
    lock(?rwlock);
    while (nreaders + nwriters) > 0:
        unlock(?rwlock);
        lock(?rwlock);
    ;
    nwriters = 1;
    unlock(?rwlock);
;
def release_wlock():
    lock(?rwlock);
    nwriters = 0;
    unlock(?rwlock);
;
```

Mesa monitor

```
def acquire_wlock():
    lock(?rwlock);
    while (nreaders + nwriters) > 0:
        wait(?wcond);
    ;
    nwriters = 1;
    unlock(?rwlock);
;
def release_wlock():
    lock(?rwlock);
    nwriters = 0;
    notifyAll(?rcond);
    notify(?wcond);
    unlock(?rwlock);
;
```

R/W lock, writer part

busy waiting

```
def acquire_wlock():
    lock(?rwlock);
    while (nreaders + nwriters) > 0:
        unlock(?rwlock);
        lock(?rwlock);
    ;
    nwriters = 1;
    unlock(?rwlock);
;
def release_wlock():
    lock(?rwlock);
    nwriters = 0;
    unlock(?rwlock);
;
```

Mesa monitor

```
def acquire_wlock():
    lock(?rwlock);
    while (nreaders + nwriters) > 0:
        wait(?wcond);
    ;
    nwriters = 1;
    unlock(?rwlock);
;
def release_wlock():
    lock(?rwlock);
    nwriters = 0;
    notifyAll(?rcond);
    notify(?wcond);
    unlock(?rwlock);
;
```

What the recruiter wanted…

```
import synch;

def T0():
    lock(?mutex);
    while not done:
        wait(?cond);
    ;
    unlock(?mutex);
;
def T1():
    lock(?mutex);
    done = True;
    notify(?cond);
    unlock(?mutex);
;
mutex = Lock();
cond = Condition(?mutex);
done = False;
spawn T0();
spawn T1();
```