CS3.301 Operating Systems and Networks

Classical Concurrency Problems and Concurrency Bugs

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Acknowledgement

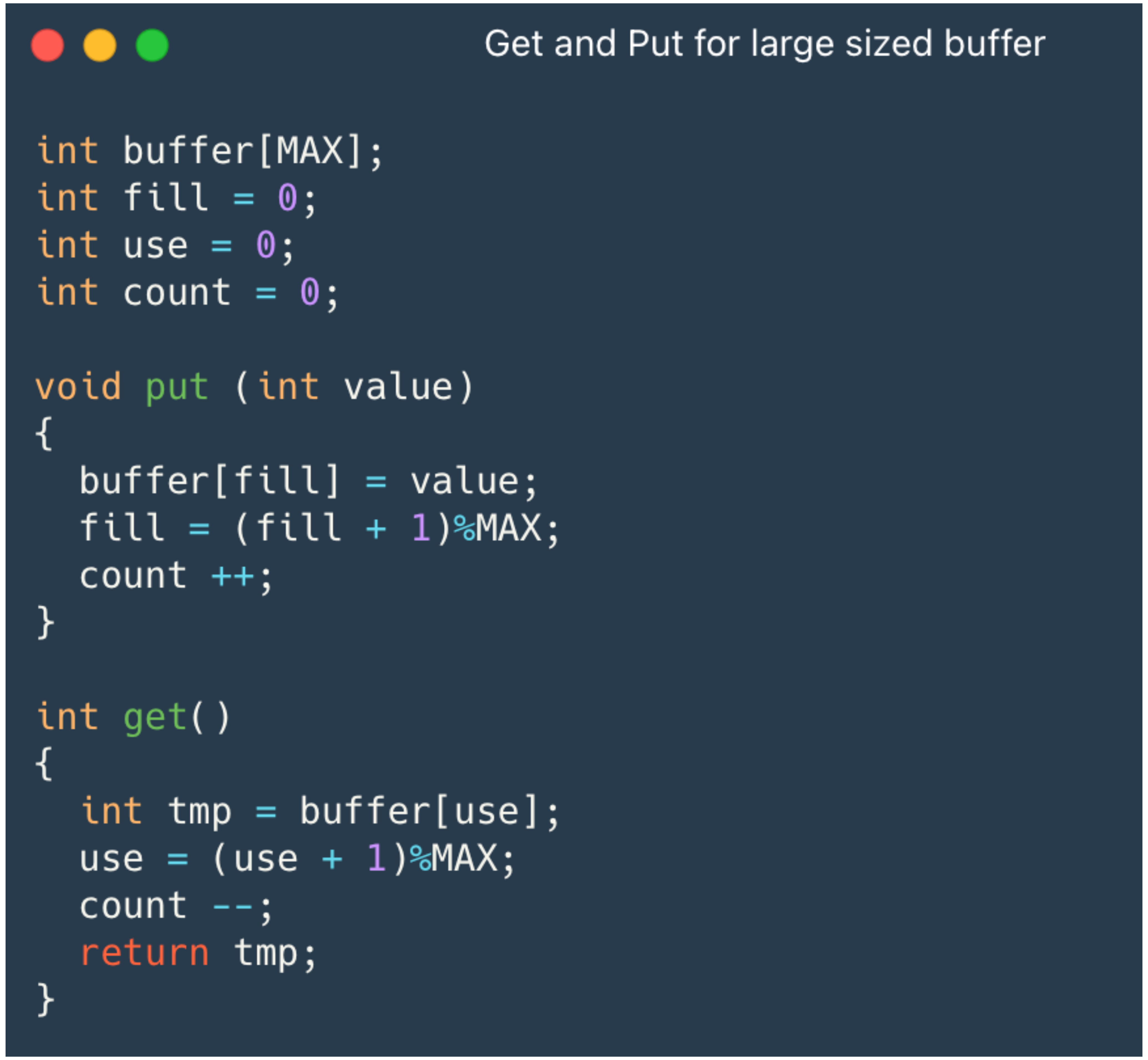
The materials used in this presentation have been gathered/adapted/generate from various sources as well as based on my own experiences and knowledge -- Karthik Vaidhyanathan

Sources:

- Operating Systems in three easy pieces by Remzi et al.

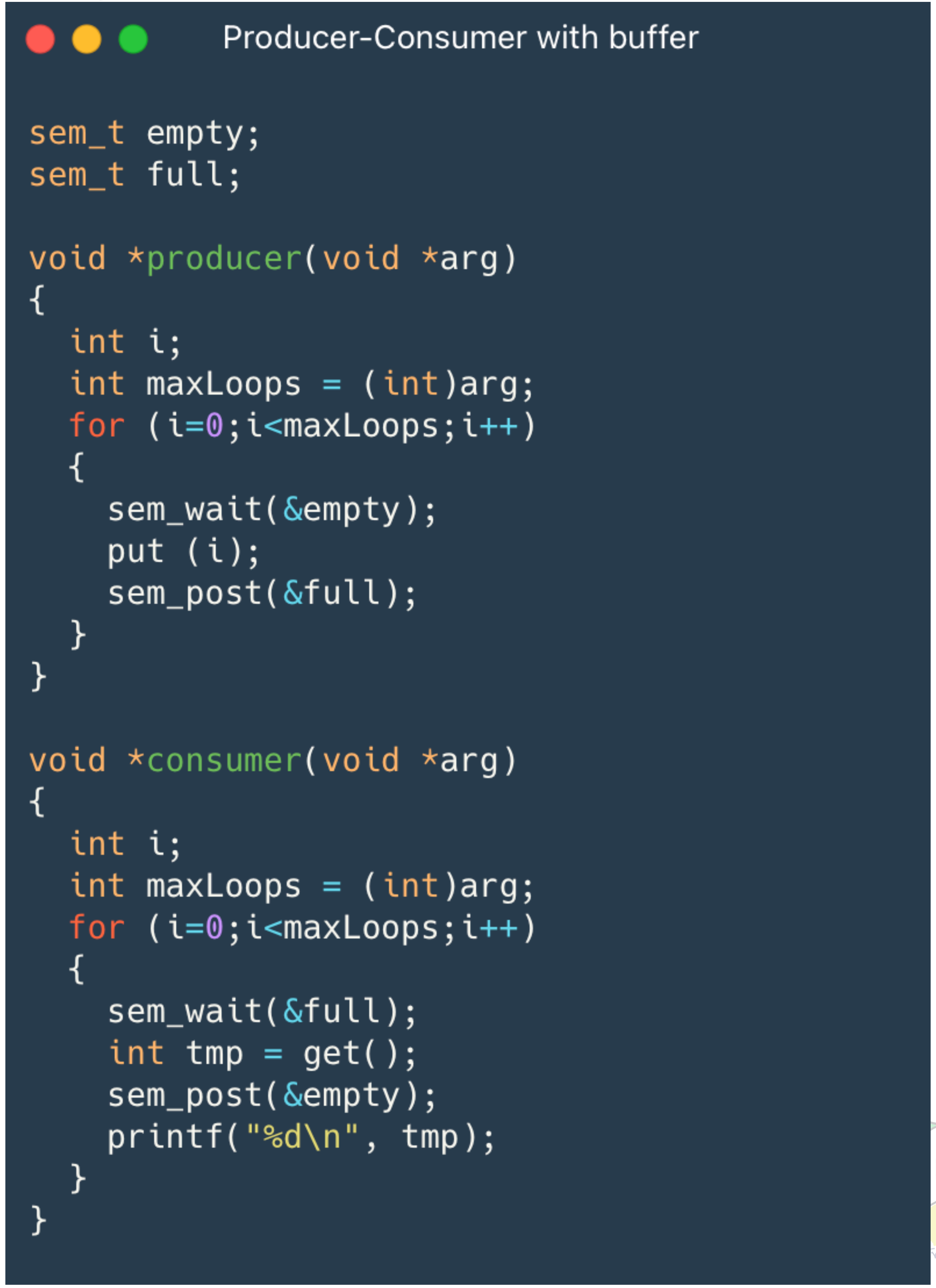
Producer Consumer Problem Using Semaphores

- Let us start with 2 semaphores: empty and wait, Buffer with MAX = 1



Get and Put for large sized buffer

```c
int buffer[MAX];
int fill = 0;
int use = 0;
int count = 0;

void put (int value)
{
  buffer[fill] = value;
  fill = (fill + 1)%MAX;
  count ++;
}

int get()
{
  int tmp = buffer[use];
  use = (use + 1)%MAX;
  count --;
  return tmp;
}
```



Producer-Consumer with buffer

```c
sem_t empty;
sem_t full;

void *producer(void *arg)
{
  int i;
  int maxLoops = (int)arg;
  for (i=0;i<maxLoops;i++)
  {
    sem_wait(&empty);
    put (i);
    sem_post(&full);
  }
}

void *consumer(void *arg)
{
  int i;
  int maxLoops = (int)arg;
  for (i=0;i<maxLoops;i++)
  {
    sem_wait(&full);
    int tmp = get();
    sem_post(&empty);
    printf("%d\n", tmp);
  }
}
```

Is our solution fine?

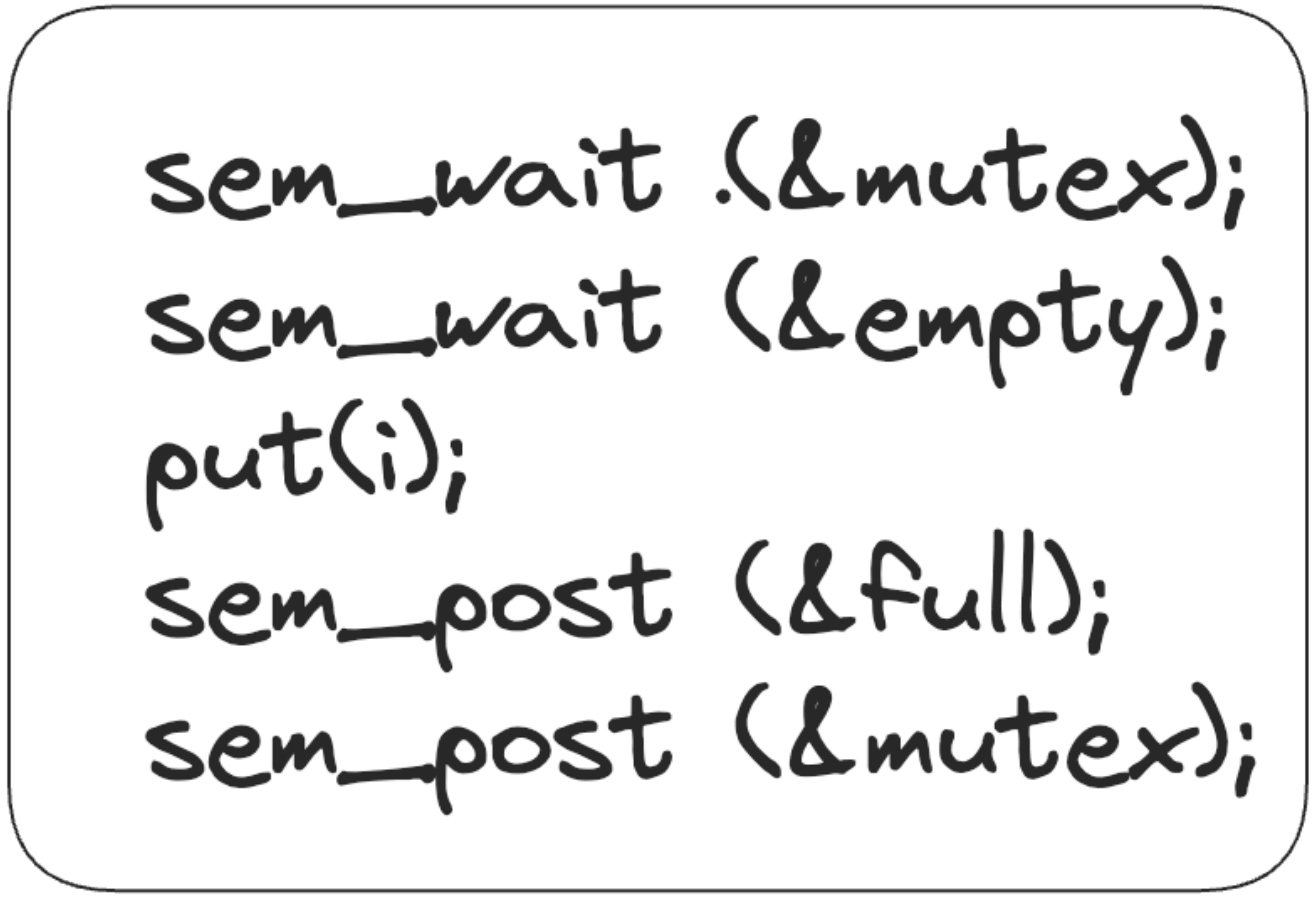
- Consider two threads (producer and consumer) on single thread
- Assume consume runs first sem_wait(&full)
  - Decrements **full (0) to -1** and waits for the thread to call post
  - Moves to a blocked state
- Producer runs, calls sem_wait (&empty)
  - **Empty (1) is decremented to 0** and proceeds to add value
  - Once done, calls post and moves consumer to ready
  - If producer runs again, it will keep looping, consumer when runs, can get the lock
- This can work for multiple producers and consumers but what **if MAX>1**

What about buffer with MAX>1

- Assume two producers, **P1 and P2**
- P1 runs first, fills the buffer entry, before updated, interrupt happens
- P2 starts to run and overwrites the value written by P1
- The reason:
  - Two producers **calling put() at the same time!!**
  - Race condition is triggered!
- Remember we have not locked get and put here. What can be done?

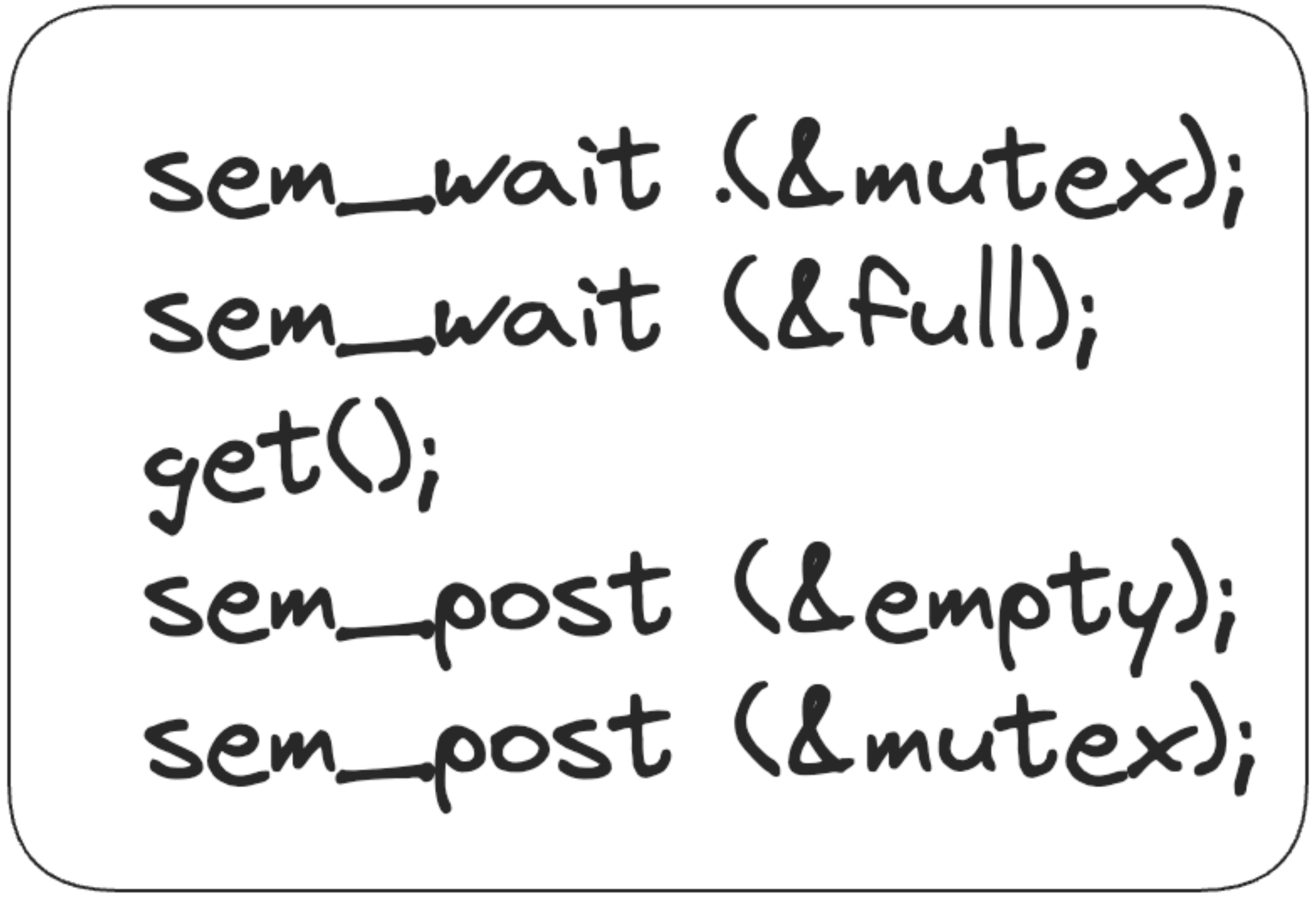
Add mutex to solve Producer-Consumer

Producer



```
sem_wait (&mutex);
sem_wait (&empty);
put(i);
sem_post (&full);
sem_post (&mutex);
```

Consumer



```
sem_wait (&mutex);
sem_wait (&full);
get();
sem_post (&empty);
sem_post (&mutex);
```

- Is there any issue with above code?
- C1 runs first gets mutex but waits on empty, P1 runs but waits for mutex - **Deadlock!!**

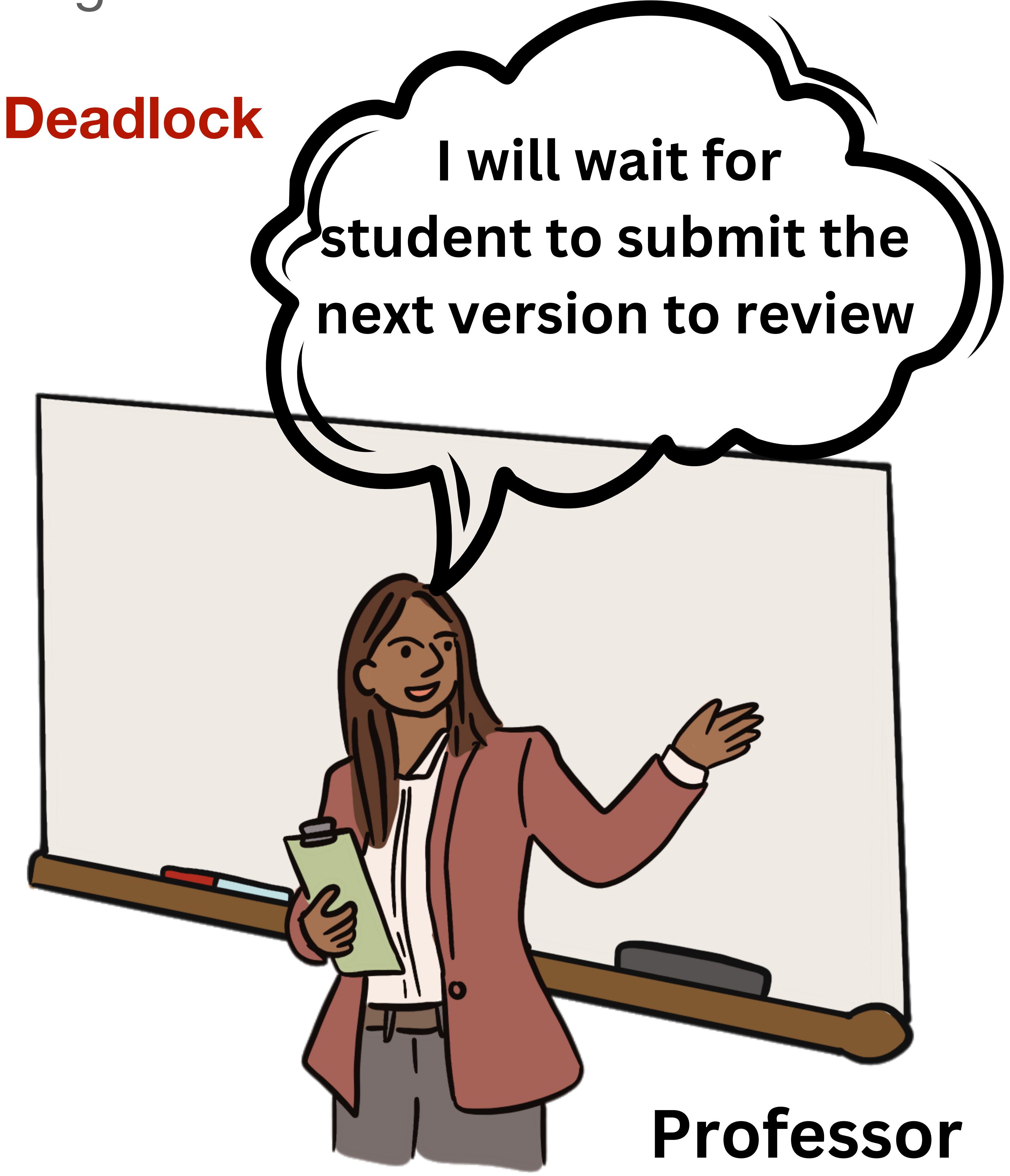
Deadlocks?

Student has submitted a draft and
Waits for review

Professor is expecting student
To submit better version to start
Reviewing

Both wait - Deadlock

Student



Professor

Producer Consumer Problem Using Semaphores

The Solution

Producer

```
sem_wait (&empty);
sem_wait (&mutex);
put(i);
sem_post (&mutex);
sem_post (&full);
```

Consumer

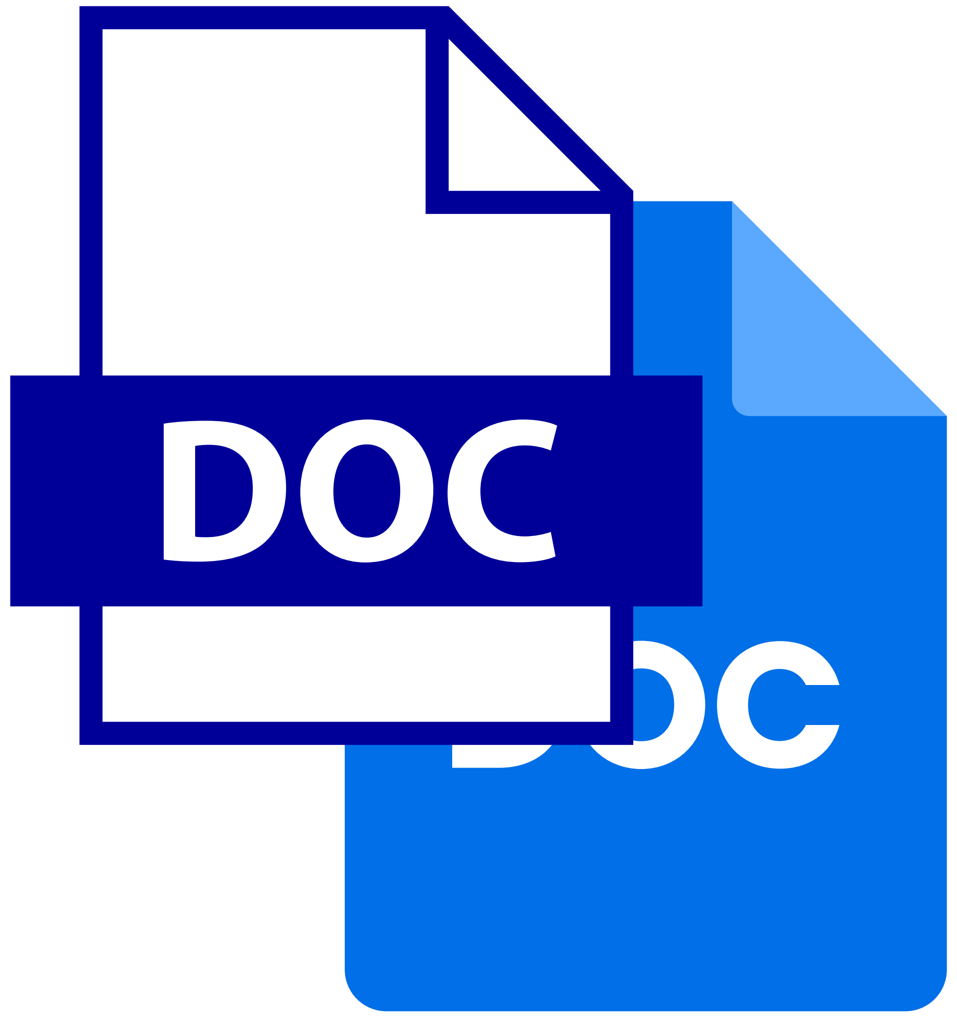
```
sem_wait (&full);
sem_wait (&mutex);
get();
sem_post (&mutex);
sem_post (&empty);
```

- Add mutex lock around put and get
- Let producer and consumer get the signal and then lock when entering CS

An Analogy

One Person writing

Many people reading at the same time

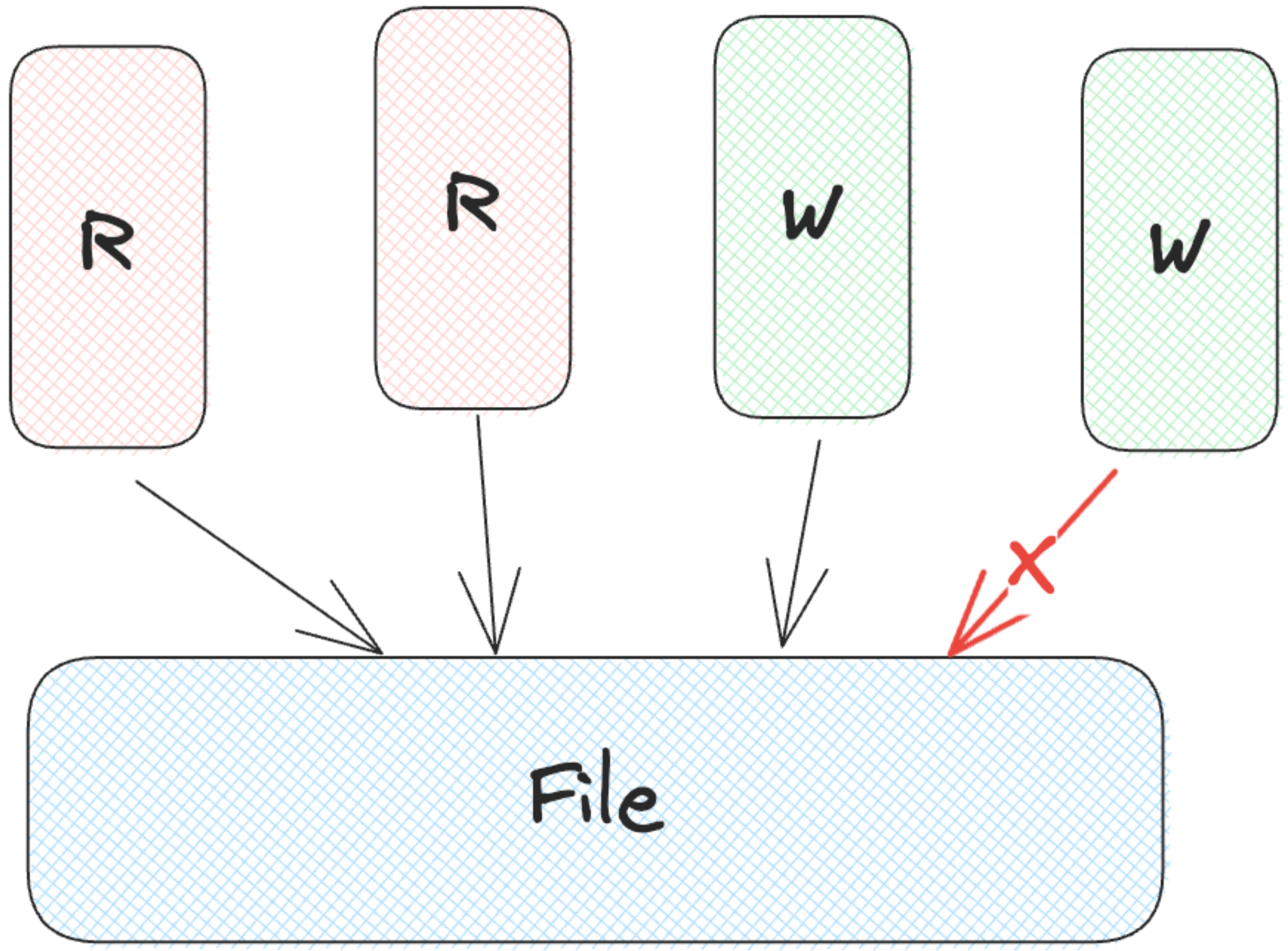


Online word processors

Databases

Readers/Writers Problem

- **Reader:** Process or thread that reads from memory
- **Writer:** Process or thread that writes on the memory
- Two readers can work on the same file at the same time
- Multiple writers cannot work on the same file at the same time

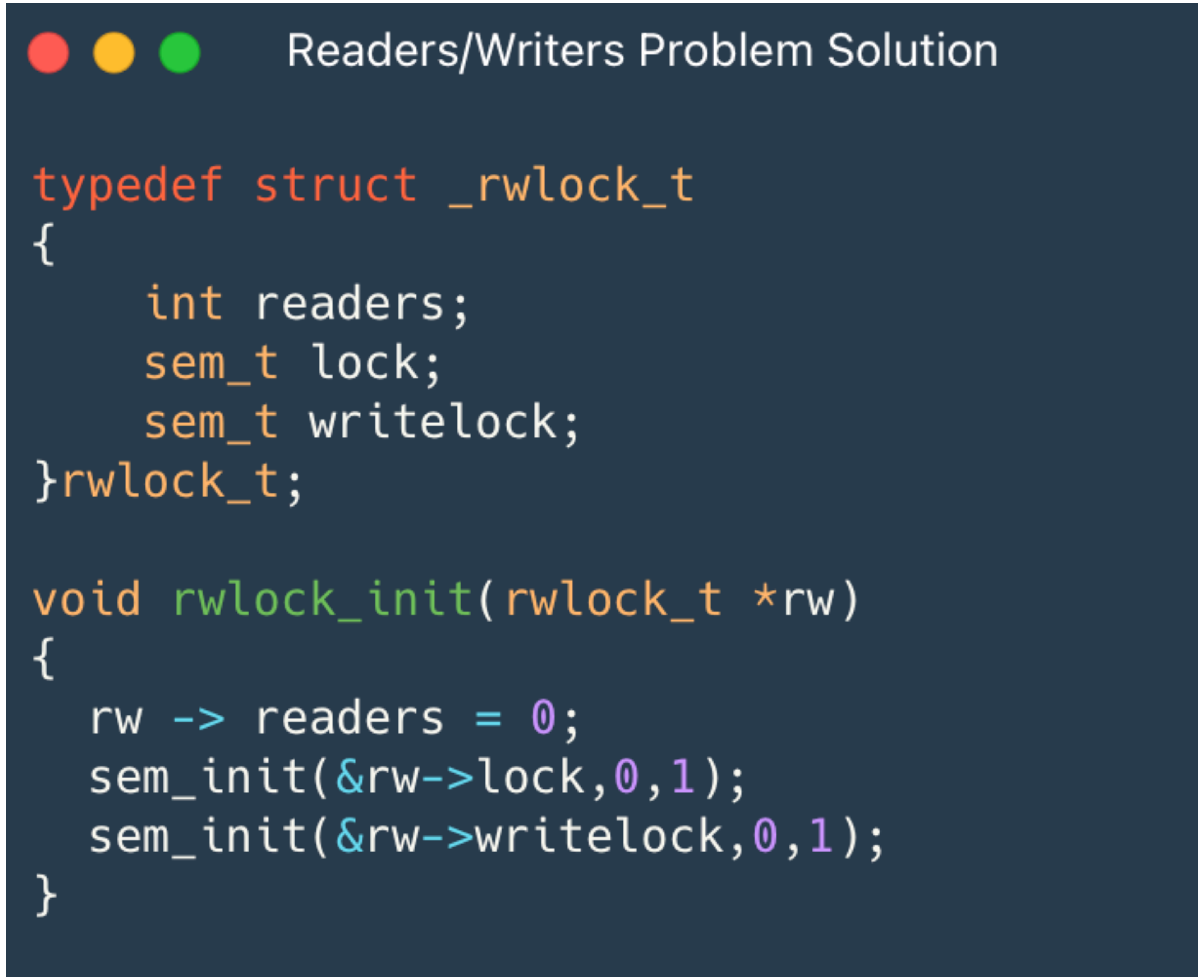


Readers/Writers Problem

Intuition

- **Only one writer can write at any point of time!**
- Reader thread can come in:
    - More readers come in, they can be allowed access
    - The moment writers come, it can be blocked
    - Once readers are done with reading, writers can start writing
- Can you think about writing a solution to this?
    - Do you foresee any challenges here?

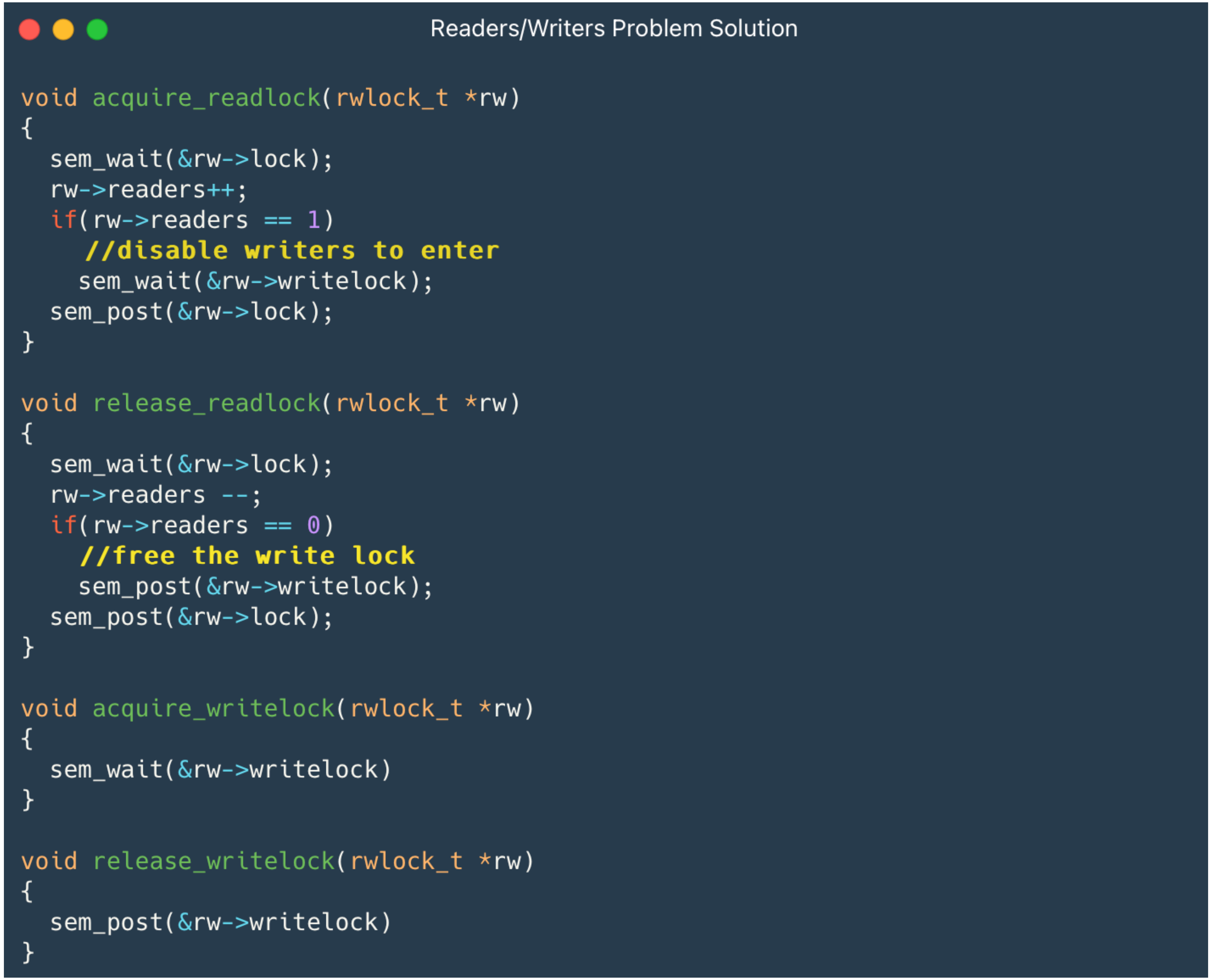
Readers/Writers Problem



Readers/Writers Problem Solution

```
typedef struct _rwlock_t
{
    int readers;
    sem_t lock;
    sem_t writelock;
}rwlock_t;

void rwlock_init(rwlock_t *rw)
{
  rw -> readers = 0;
  sem_init(&rw->lock,0,1);
  sem_init(&rw->writelock,0,1);
}
```

Readers/writers Problem Solution



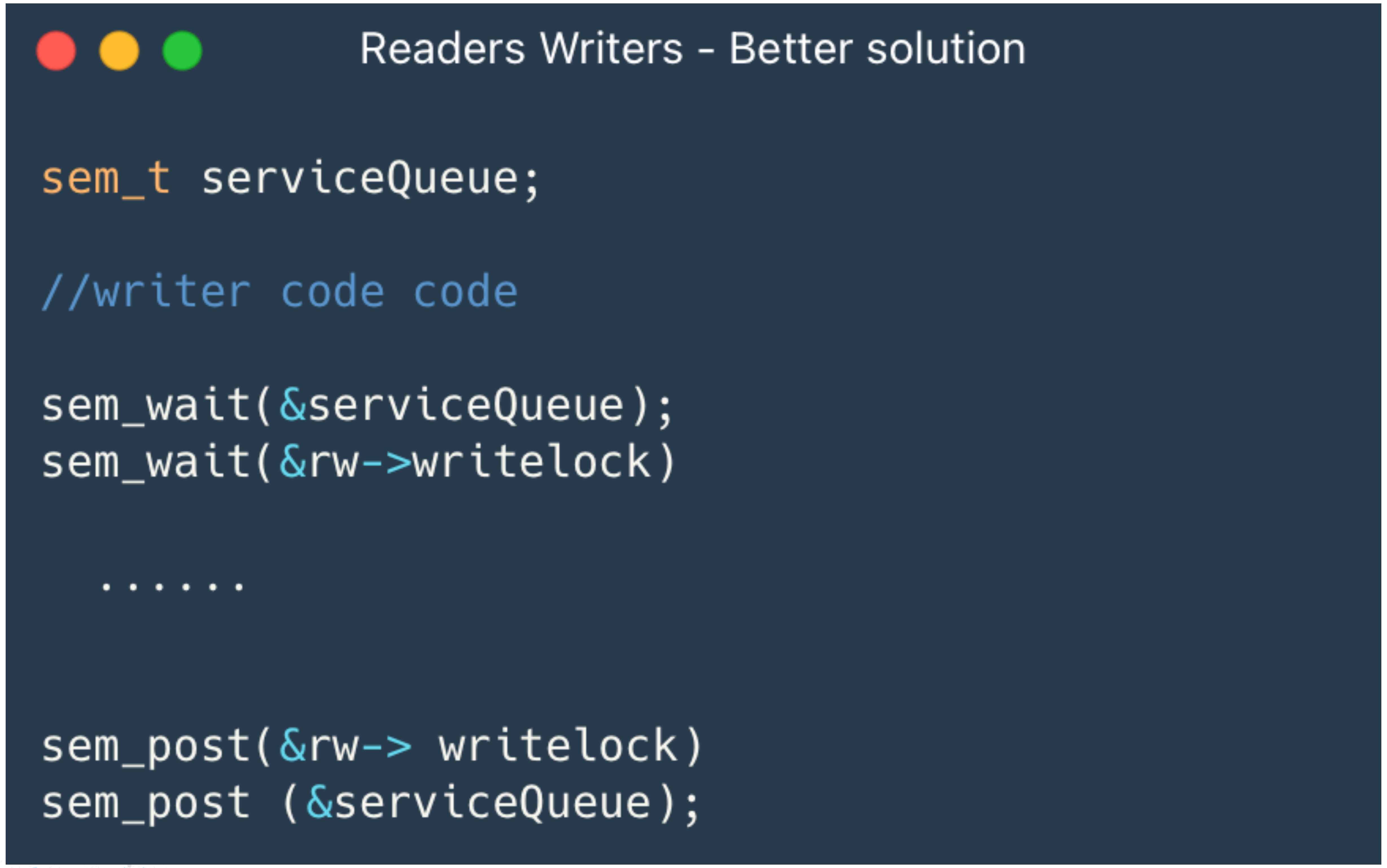
Readers/Writers Problem Solution

```
void acquire_readlock(rwlock_t *rw)
{
  sem_wait(&rw->lock);
  rw->readers++;
  if(rw->readers == 1)
    //disable writers to enter
    sem_wait(&rw->writelock);
  sem_post(&rw->lock);
}

void release_readlock(rwlock_t *rw)
{
  sem_wait(&rw->lock);
  rw->readers --;
  if(rw->readers == 0)
    //free the write lock
    sem_post(&rw->writelock);
  sem_post(&rw->lock);
}

void acquire_writelock(rwlock_t *rw)
{
  sem_wait(&rw->writelock)
}

void release_writelock(rwlock_t *rw)
{
  sem_post(&rw->writelock)
}
```

Writers Starve!!!

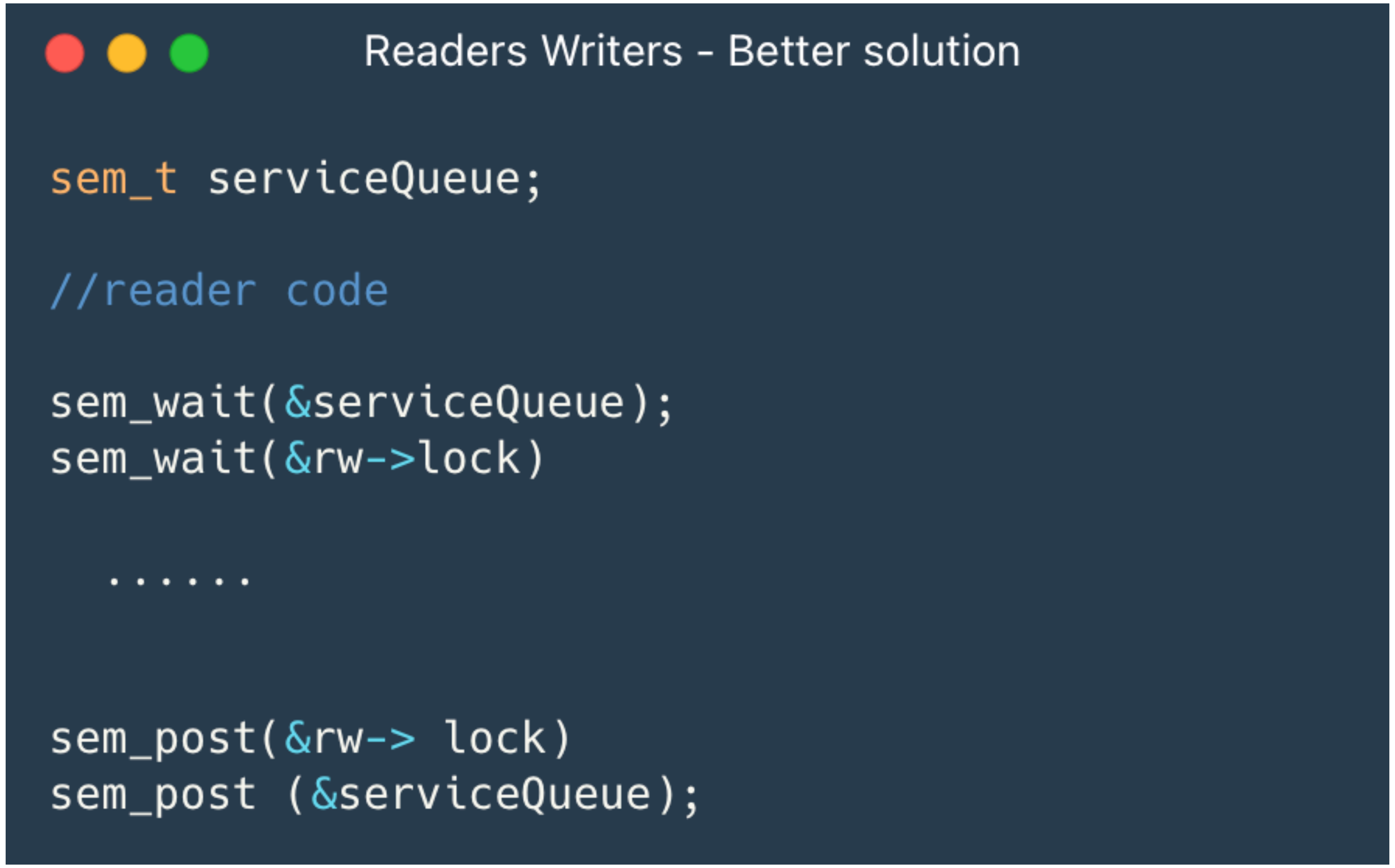
Readers/Writers Problem Solution

Add a lock that can act as priority common to both



```
sem_t serviceQueue;

//writer code code

sem_wait(&serviceQueue);
sem_wait(&rw->writelock)

  ......


sem_post(&rw-> writelock)
sem_post (&serviceQueue);
```

Writer

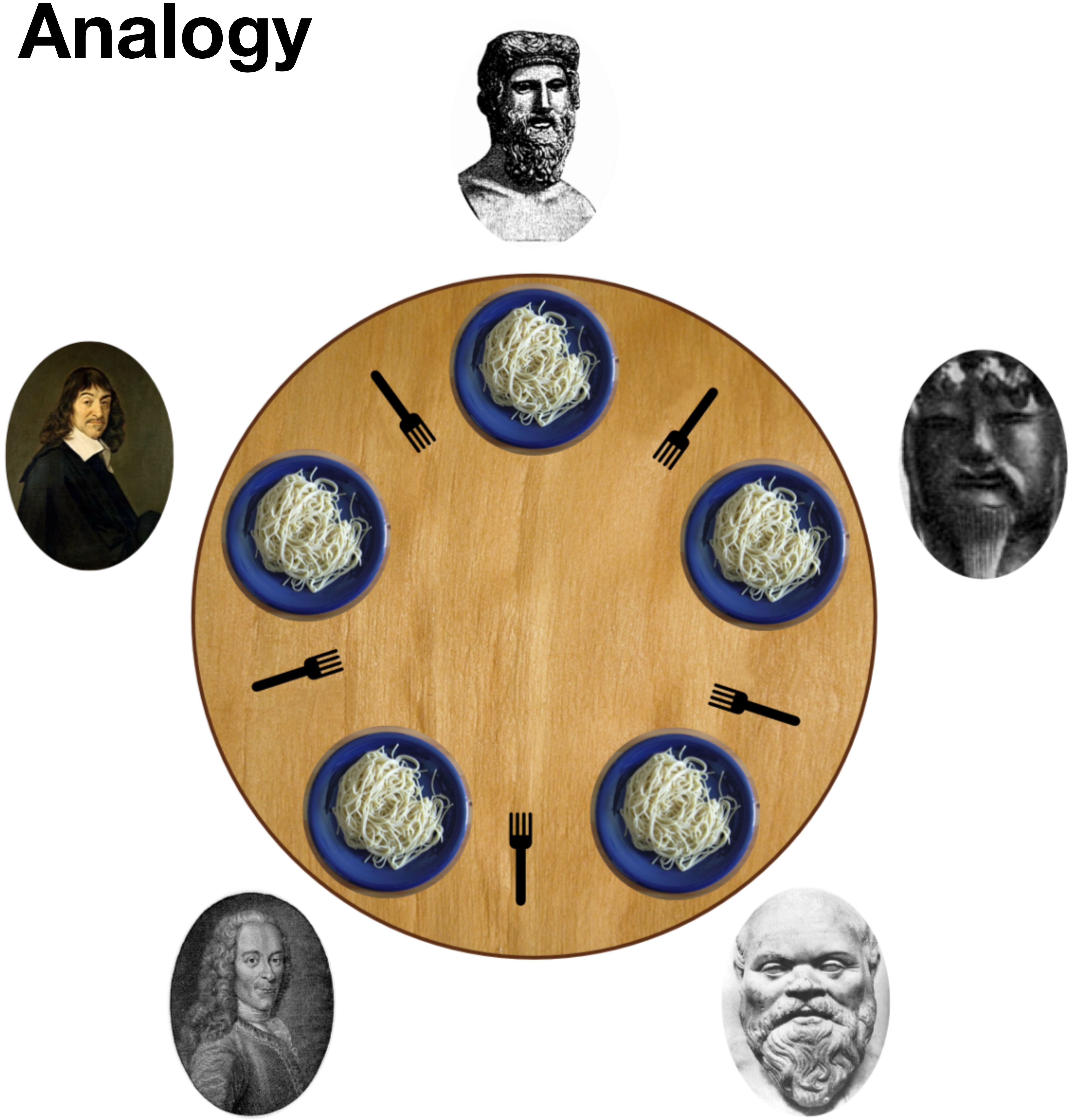


```
sem_t serviceQueue;

//reader code

sem_wait(&serviceQueue);
sem_wait(&rw->lock)

  ......


sem_post(&rw-> lock)
sem_post (&serviceQueue);
```

Reader

The Dinning Philosophers

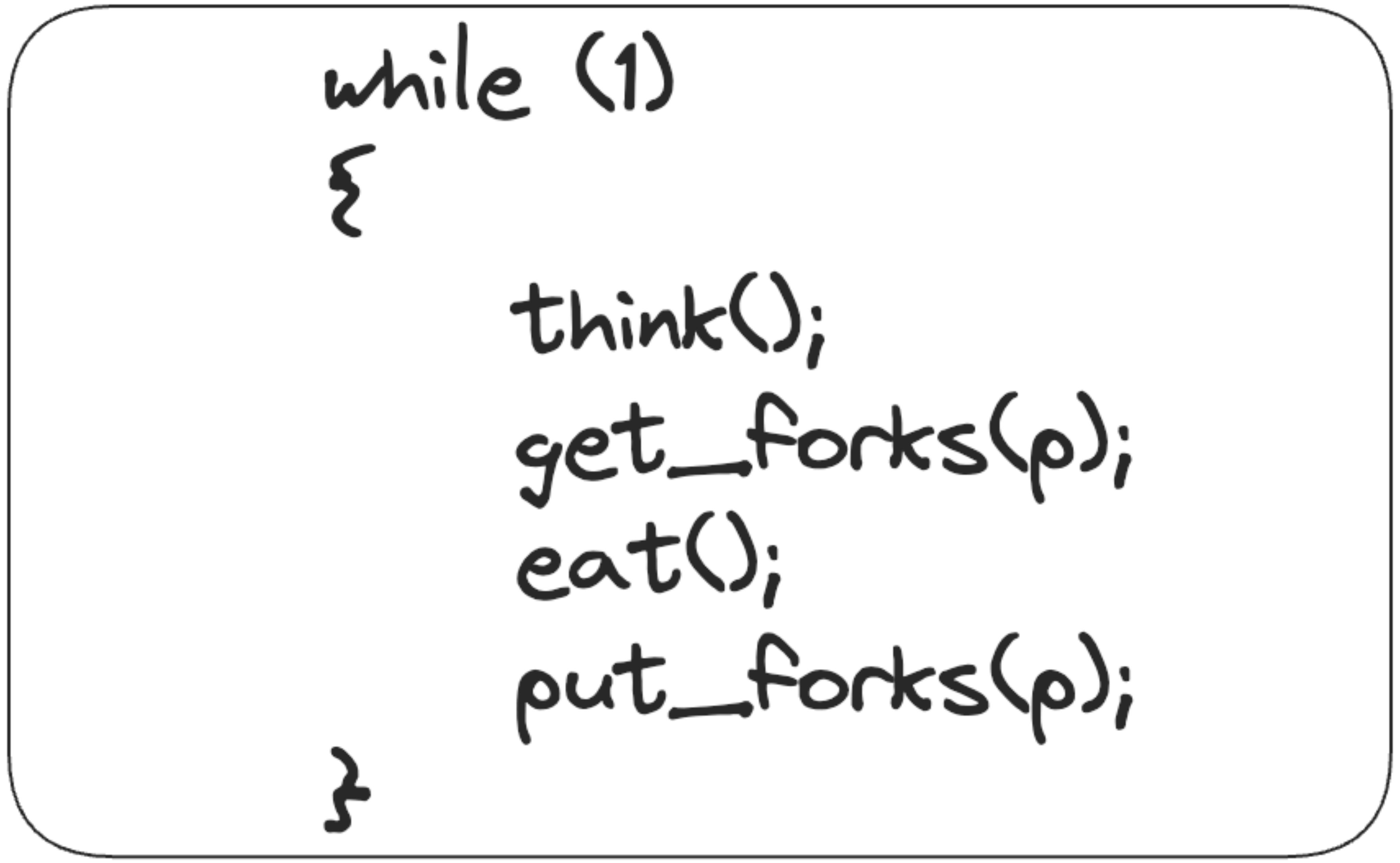
An Analogy



- Five philosophers sit around a dinning table
- They think for sometime and eat spaghetti for sometime!
- There is one fork on the left and one on the right of each
- If they get two forks, then they can start eating, once done, they can keep it down
- How to solve it?

Image source: Wikipedia

Classic Problem: Dining Philosophers

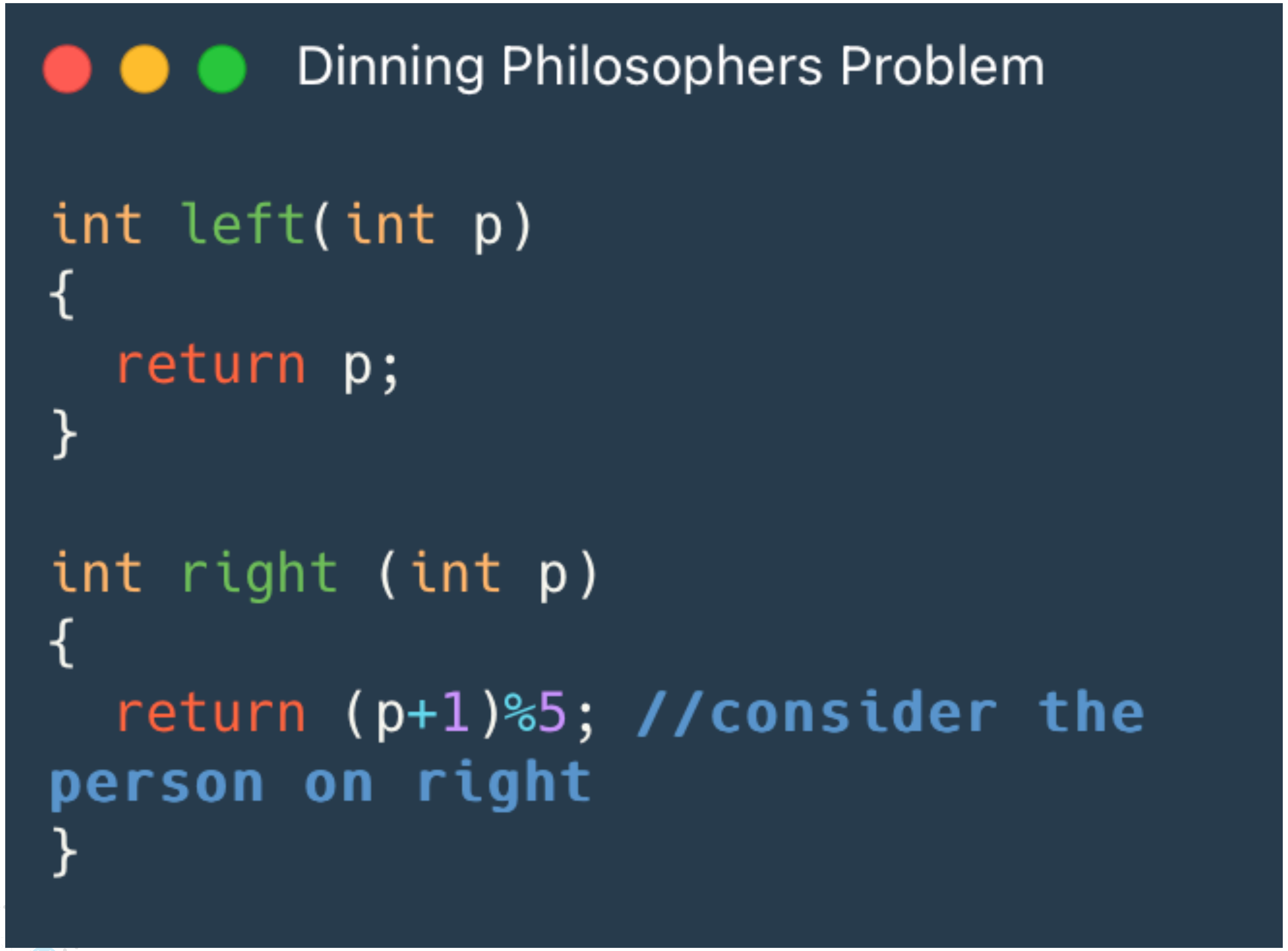


```
while (1)
{
        think();
        get_forks(p);
        eat();
        put_forks(p);
}
```

- Each philosopher is a unique thread with an id (p = 0 to 4);
- Get forks and put forks needs to be written by ensuring there is no deadlock
    - is there a **possibility of deadlock?** Why?
    - Also **no philosopher should starve!**
- Can you think of implementing get_forks(p) and put_forks(p)?

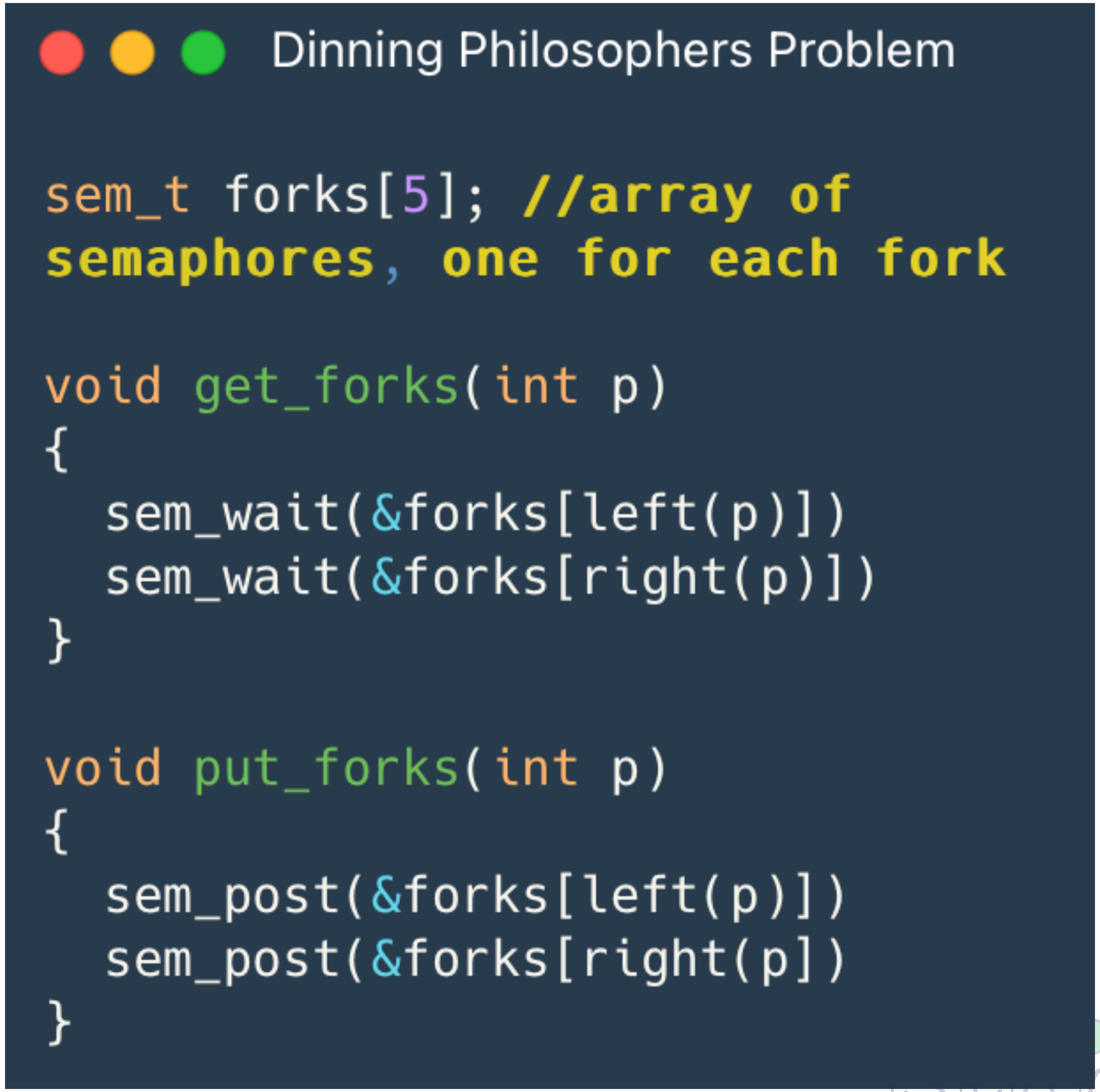
Possible Solution

All semaphores initiated to 1



Dinning Philosophers Problem

```
int left(int p)
{
   return p;
}

int right (int p)
{
   return (p+1)%5; //consider the
person on right
}
```

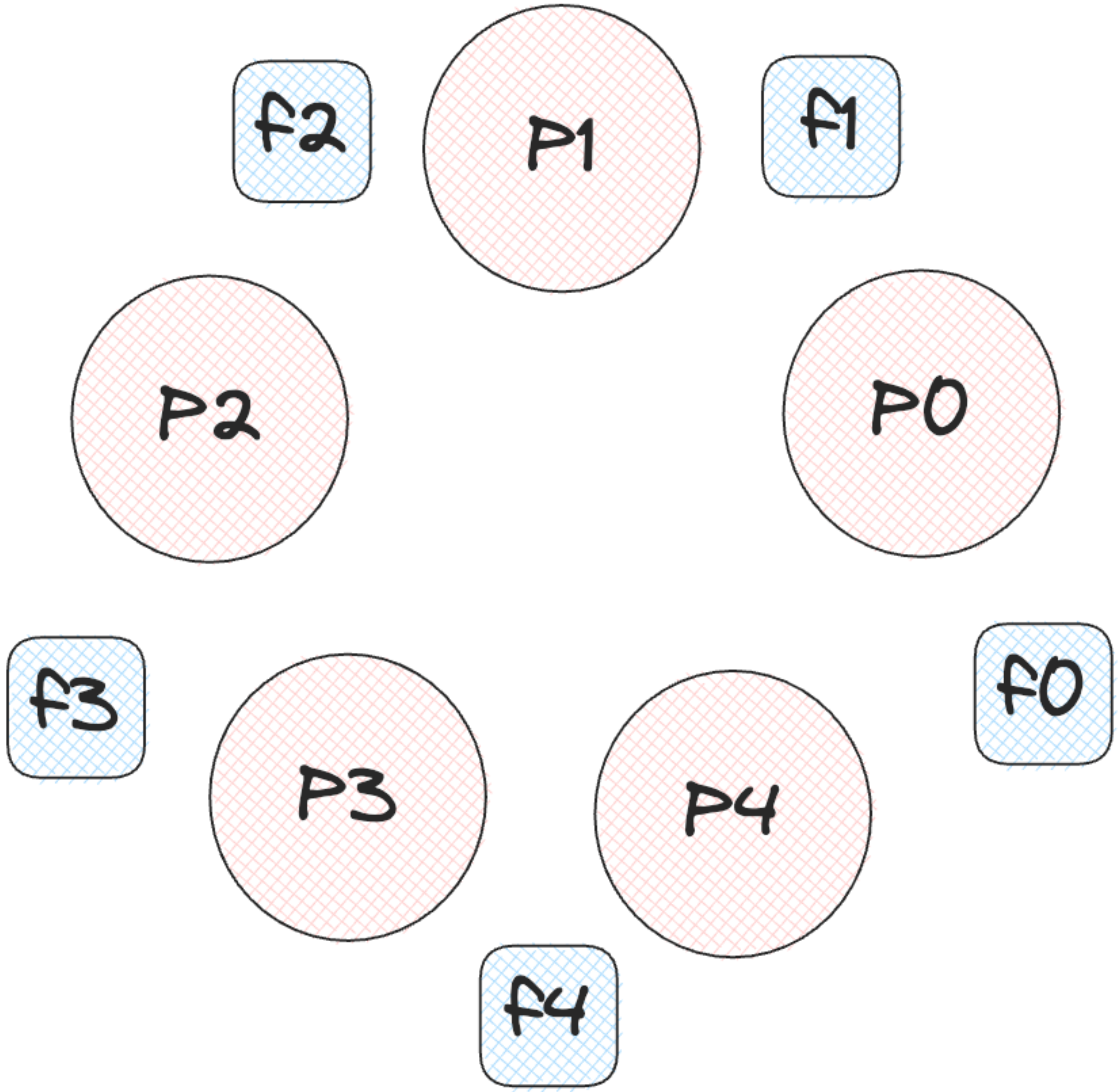


Dinning Philosophers Problem

```
sem_t forks[5]; //array of
semaphores, one for each fork

void get_forks(int p)
{
   sem_wait(&forks[left(p)])
   sem_wait(&forks[right(p)])
}

void put_forks(int p)
{
   sem_post(&forks[left(p)])
   sem_post(&forks[right(p])
}
```

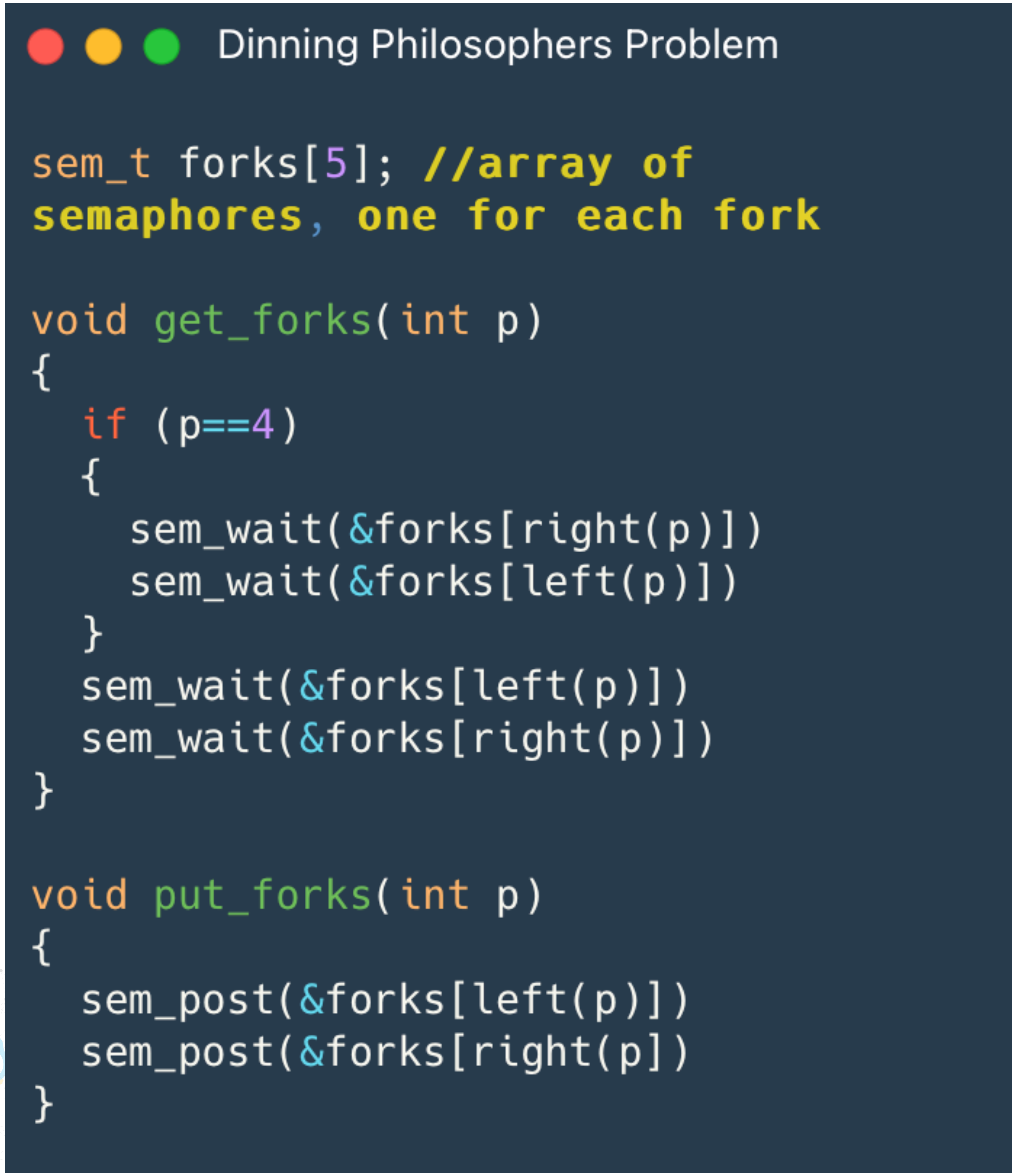
Any issues here? **Deadlock!!, How?**

How deadlock happened?



- Each philosopher is one thread and they start running
- The first philosopher (0) has wait on 1, gets it (since initial semaphore is 1)
- Immidiately second philosopher (1) runs, wait on 0, but gets on right
- Third will run, waits on 2nd fork but gets the 4th one
- Fourth will run, waits on third but waits on 0
- **All philosophers wait for their left fork and we have a deadlock**

Possible Solution

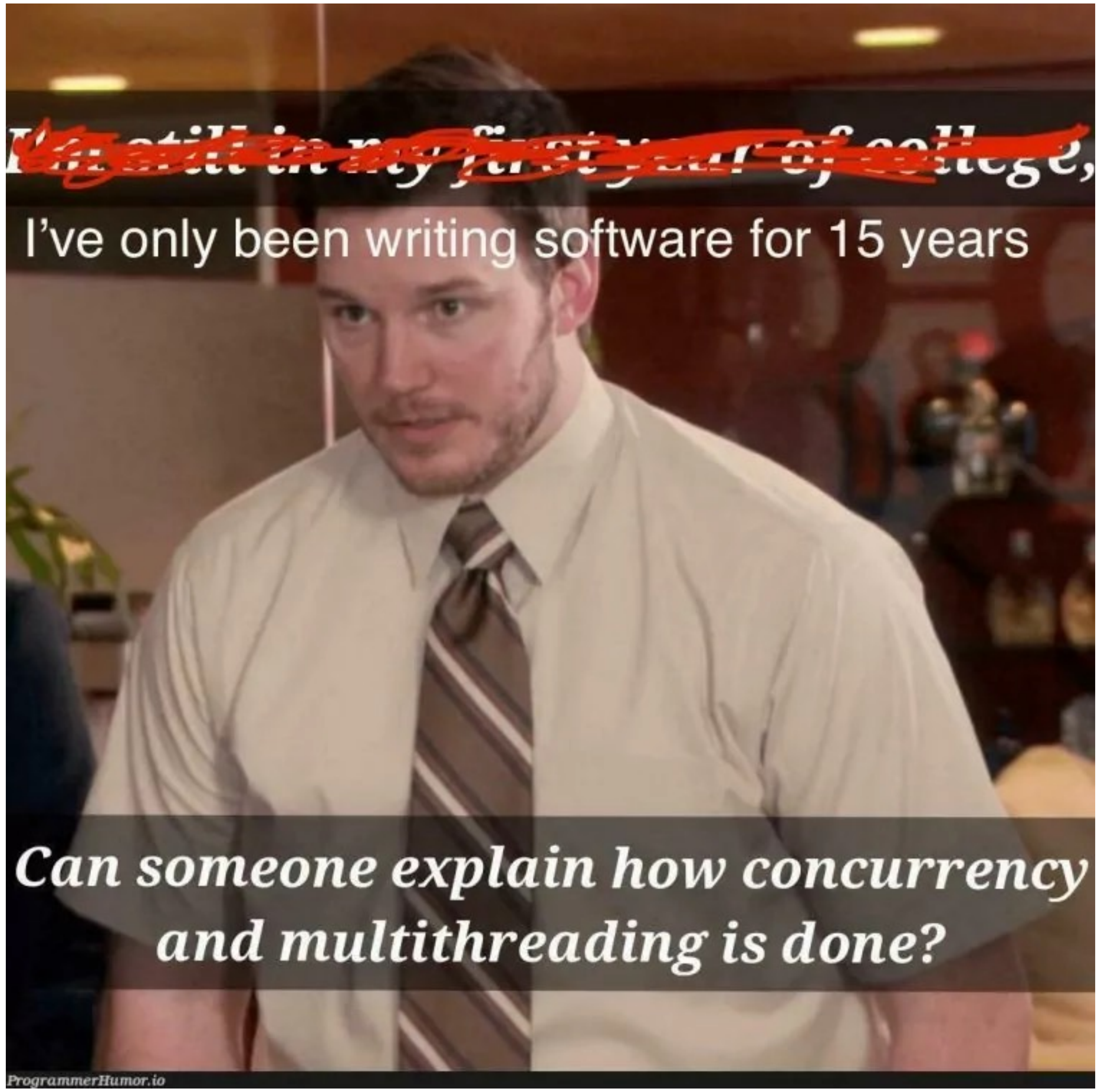


Dinning Philosophers Problem

```
sem_t forks[5]; //array of
semaphores, one for each fork

void get_forks(int p)
{
   if (p==4)
   {
      sem_wait(&forks[right(p)])
      sem_wait(&forks[left(p)])
   }
   sem_wait(&forks[left(p)])
   sem_wait(&forks[right(p)])
}

void put_forks(int p)
{
   sem_post(&forks[left(p)])
   sem_post(&forks[right(p])
}
```

- Change the order in which they eat
- Philosopher 4 acquires the fork in a different order
- There won’t be a situation in which one philosopher grabs one and has to wait for other
- **The cycle of waiting is broken**
- More solutions exist!

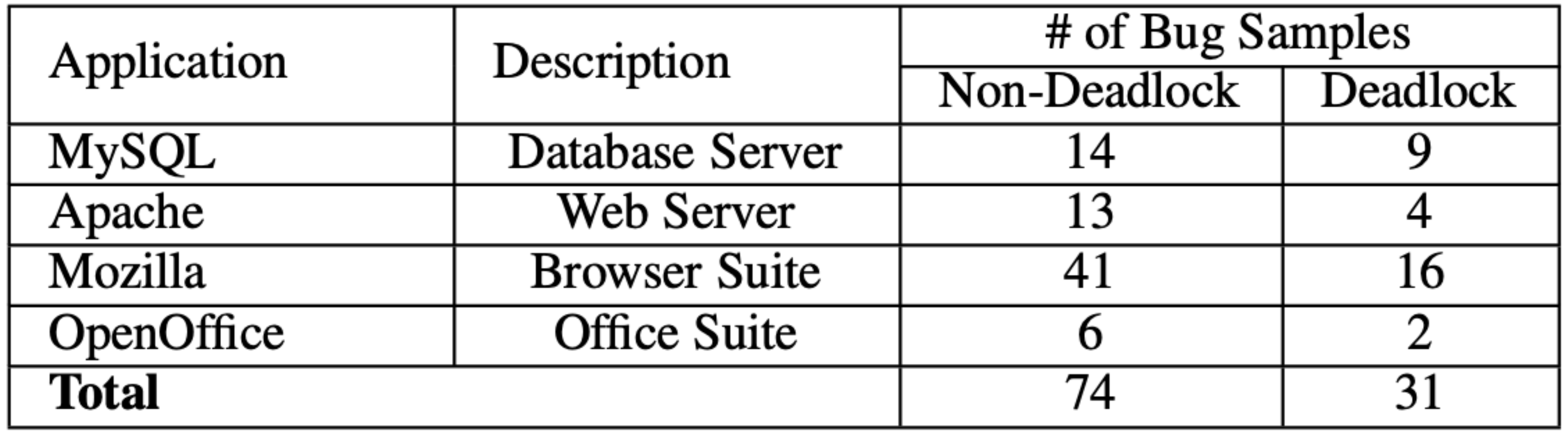
Concurrency Can be tricky!


~~I'm still in my first year of college,~~
I've only been writing software for 15 years
Can someone explain how concurrency and multithreading is done?
ProgrammerHumor.io

There are some common **Concurrency Bugs** that can help identify some common bugs

Types of Bugs

- Bugs are very non-deterministic - Occurrence order cannot be fixed
- Two types of bugs
  - **Non-deadlock bugs**: Incorrect results when threads execute
  - **Deadlock bugs**: Threads keep waiting for each other

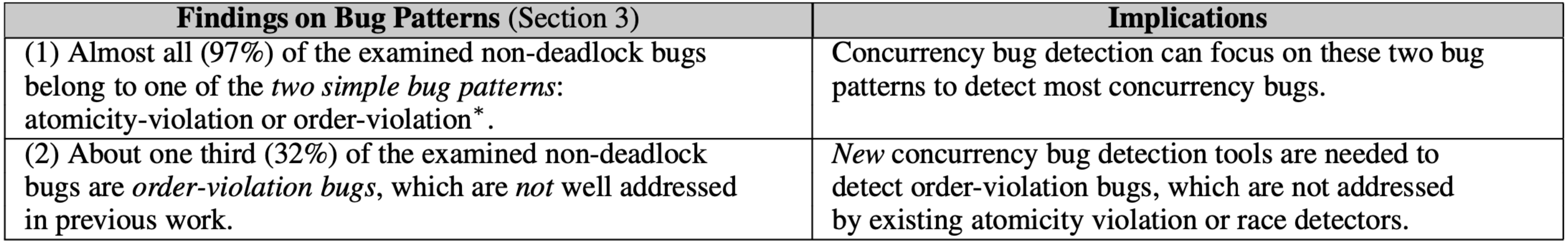


Application	Description	# of Bug Samples	
		Non-Deadlock	Deadlock
MySQL	Database Server	14	9
Apache	Web Server	13	4
Mozilla	Browser Suite	41	16
OpenOffice	Office Suite	6	2
Total		74	31

Shan Lu, Soyeon Park, Eunsoo Seo, and Yuanyuan Zhou. 2008. **Learning from mistakes: a comprehensive study on real world concurrency bug characteristics,** ASPLOS, 2008

Source: https://pages.cs.wisc.edu/~shanlu/paper/asplos122-lu.pdf

Non-deadlock Bugs



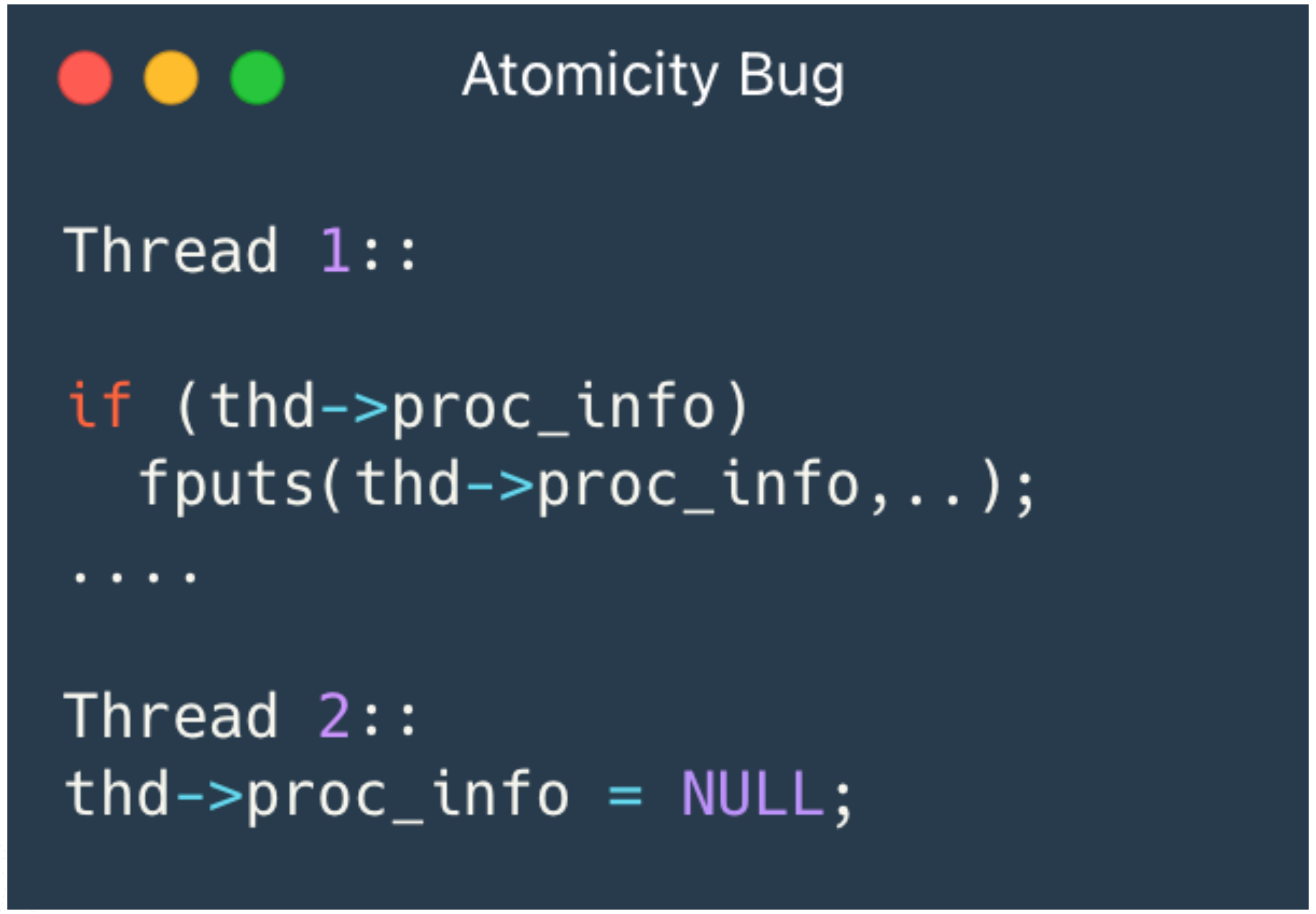
Findings on Bug Patterns (Section 3)	**Implications**
(1) Almost all (97%) of the examined non-deadlock bugs belong to one of the *two simple bug patterns*: atomicity-violation or order-violation*.	Concurrency bug detection can focus on these two bug patterns to detect most concurrency bugs.
(2) About one third (32%) of the examined non-deadlock bugs are *order-violation bugs*, which are *not* well addressed in previous work.	*New* concurrency bug detection tools are needed to detect order-violation bugs, which are not addressed by existing atomicity violation or race detectors.

Non-deadlock bugs make the majority of the bugs among concurrency bugs

- Two types of non-deadlock bugs
  - Atomicity violation bugs
  - Order violation bugs

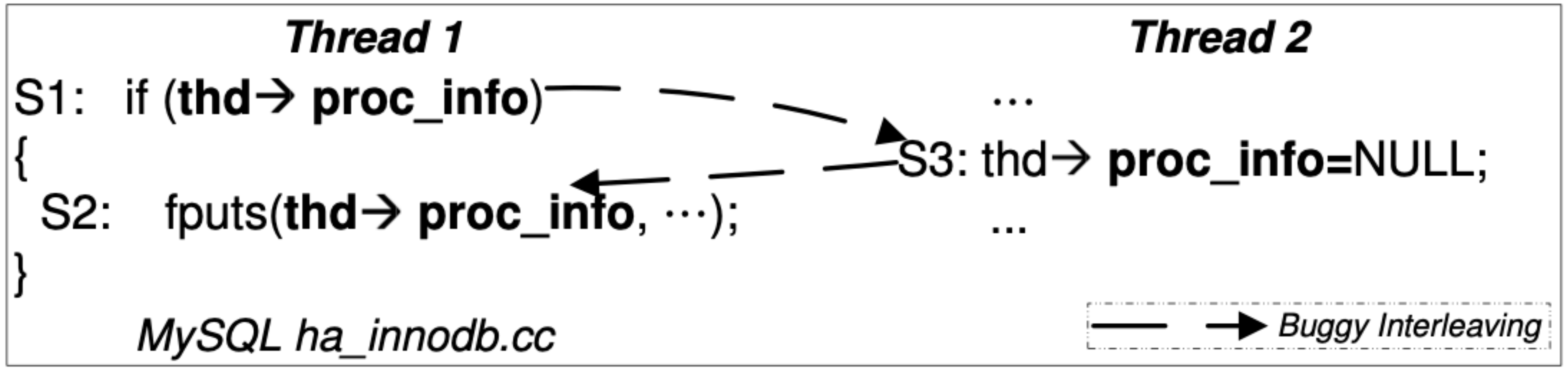
Atomicity Bugs

- Atomicity assumptions made during development are violated during execution of threads
- **Example:** From MySQL where one thread reads and modifies a shared variable while other tries to modify it



Atomicity Bug

```
Thread 1::

if (thd->proc_info)
  fputs(thd->proc_info,..);
....

Thread 2::
thd->proc_info = NULL;
```



Thread 1

S1: if (**thd→ proc_info**)

{

S2: fputs(**thd→ proc_info**, ⋯);

}

Thread 2

…

S3: thd→ **proc_info=**NULL;

…

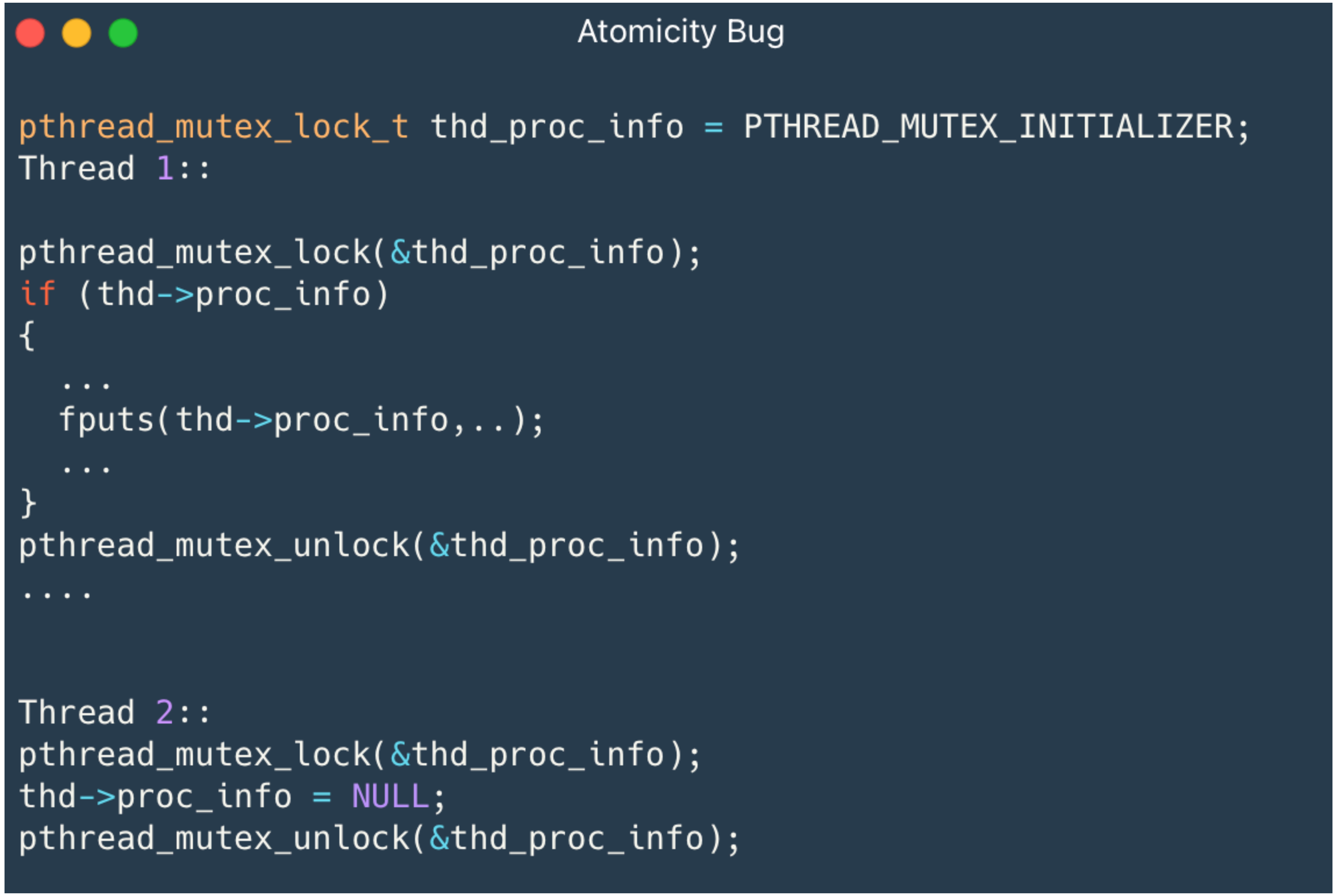
MySQL ha_innodb.cc

Buggy Interleaving

How to go about solving it?

Atomicity Bugs

Use locks when accessing shared data



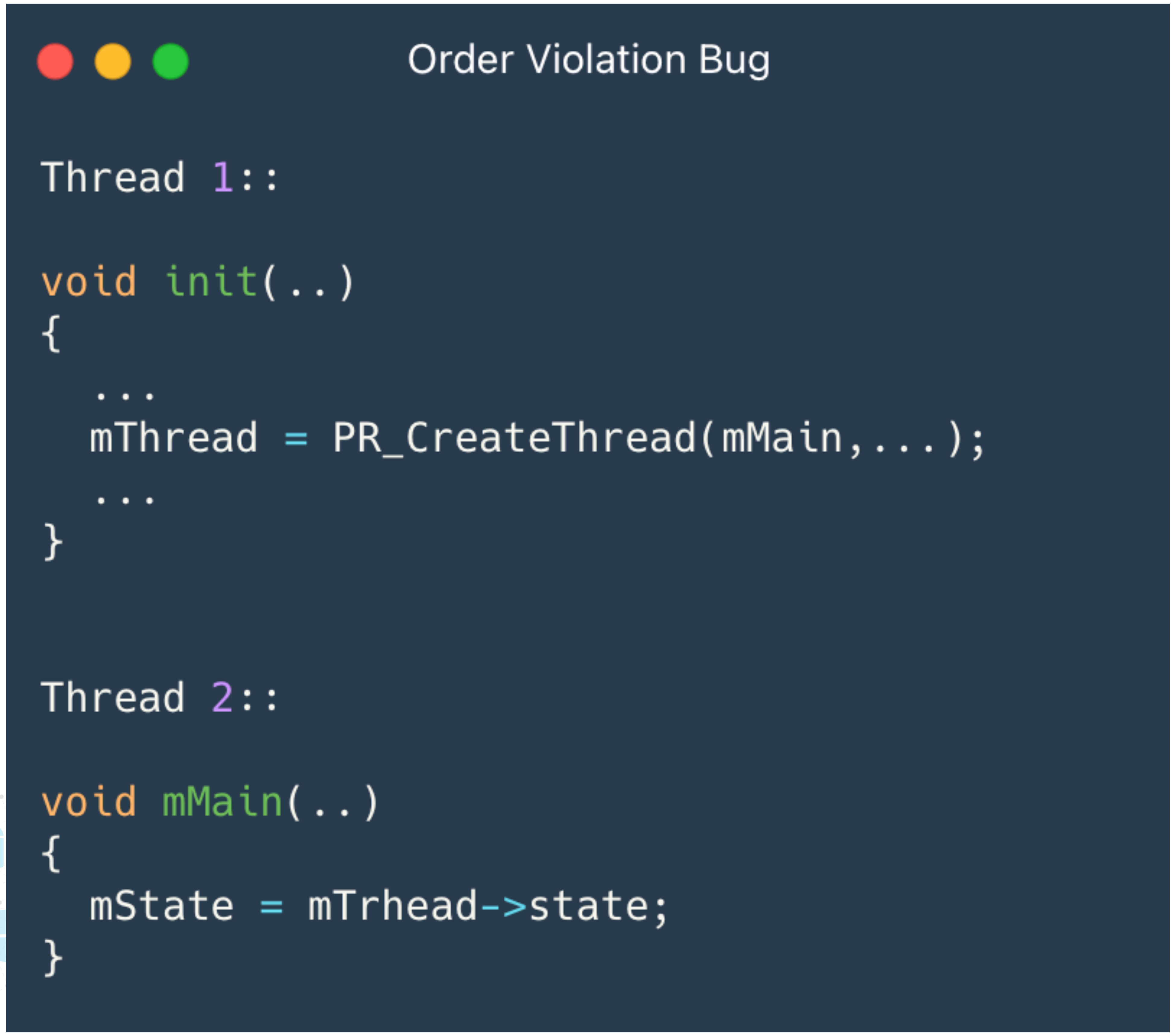
Atomicity Bug

```
pthread_mutex_lock_t thd_proc_info = PTHREAD_MUTEX_INITIALIZER;
Thread 1::

pthread_mutex_lock(&thd_proc_info);
if (thd->proc_info)
{
   ...
   fputs(thd->proc_info,..);
   ...
}
pthread_mutex_unlock(&thd_proc_info);
....


Thread 2::
pthread_mutex_lock(&thd_proc_info);
thd->proc_info = NULL;
pthread_mutex_unlock(&thd_proc_info);
```

Order Violation Bugs

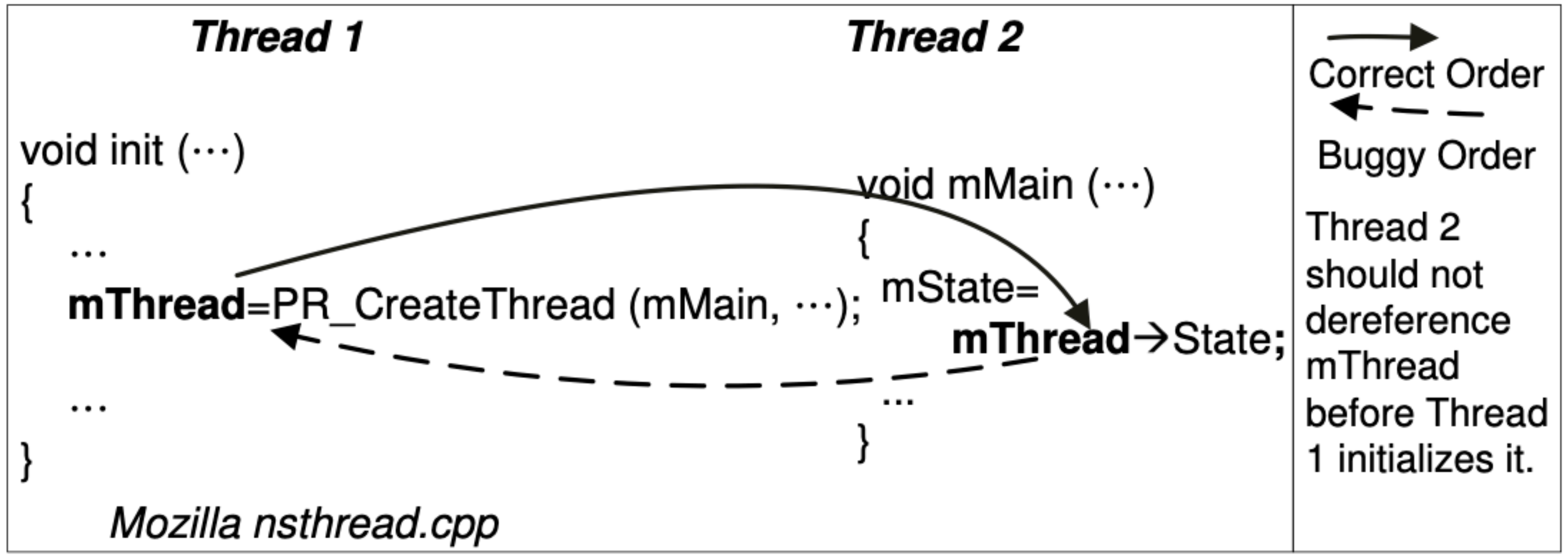
- Desired/assumed order of execution of memory access is violated during concurrent execution of threads

- **Example:** Assume thread 1 and thread 2. Thread 2 may assume that thread 1 has already run



Order Violation Bug

```
Thread 1::

void init(..)
{
   ...
   mThread = PR_CreateThread(mMain,...);
   ...
}


Thread 2::

void mMain(..)
{
   mState = mTrhead->state;
}
```



Thread 1

void init (···)
{
...
mThread=PR_CreateThread (mMain, ···);
...
}

Thread 2

void mMain (···)
{
mState=
mThread→State;
...
}

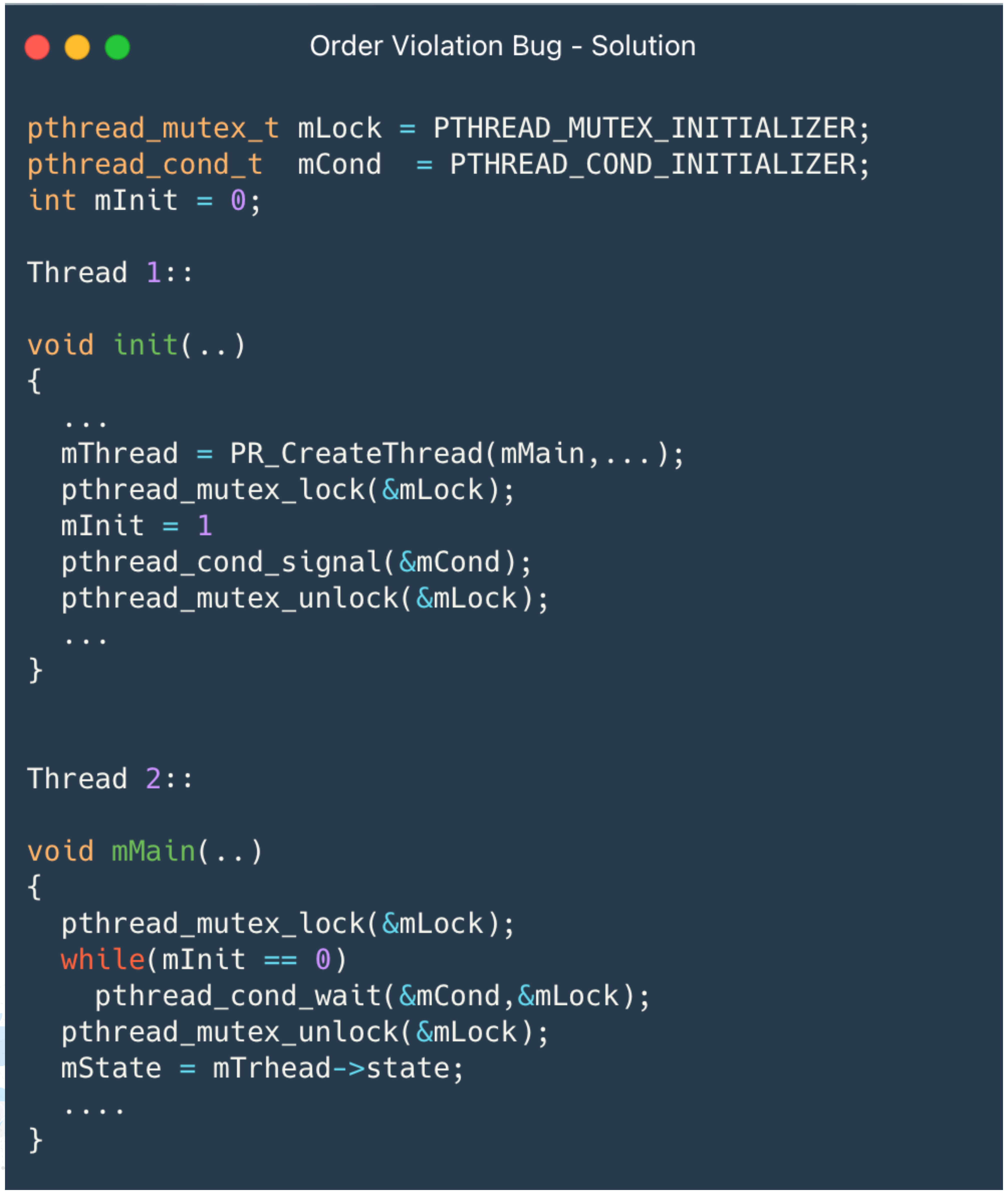
Thread 2 should not dereference mThread before Thread 1 initializes it.

Mozilla nsthread.cpp

How to go about solving it?

Order Violation Bugs

Use condition variables or semaphores

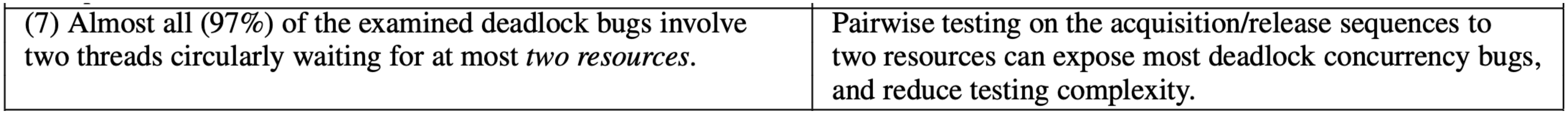


Order Violation Bug - Solution

```
pthread_mutex_t mLock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t  mCond  = PTHREAD_COND_INITIALIZER;
int mInit = 0;

Thread 1::

void init(..)
{
  ...
  mThread = PR_CreateThread(mMain,...);
  pthread_mutex_lock(&mLock);
  mInit = 1
  pthread_cond_signal(&mCond);
  pthread_mutex_unlock(&mLock);
  ...
}


Thread 2::

void mMain(..)
{
  pthread_mutex_lock(&mLock);
  while(mInit == 0)
    pthread_cond_wait(&mCond,&mLock);
  pthread_mutex_unlock(&mLock);
  mState = mTrhead->state;
  ....
}
```

- Use condition variables
  - Dependant thread can wait for dependency operation to be completed
  - Use combination of wait and signal
  - Semaphores can also be used here!
- **Remember:** Locks are still needed to handle the shared variable operation

Deadlock Bugs



(7) Almost all (97%) of the examined deadlock bugs involve two threads circularly waiting for at most *two resources*.	Pairwise testing on the acquisition/release sequences to two resources can expose most deadlock concurrency bugs, and reduce testing complexity.

Thread 1

```
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
```

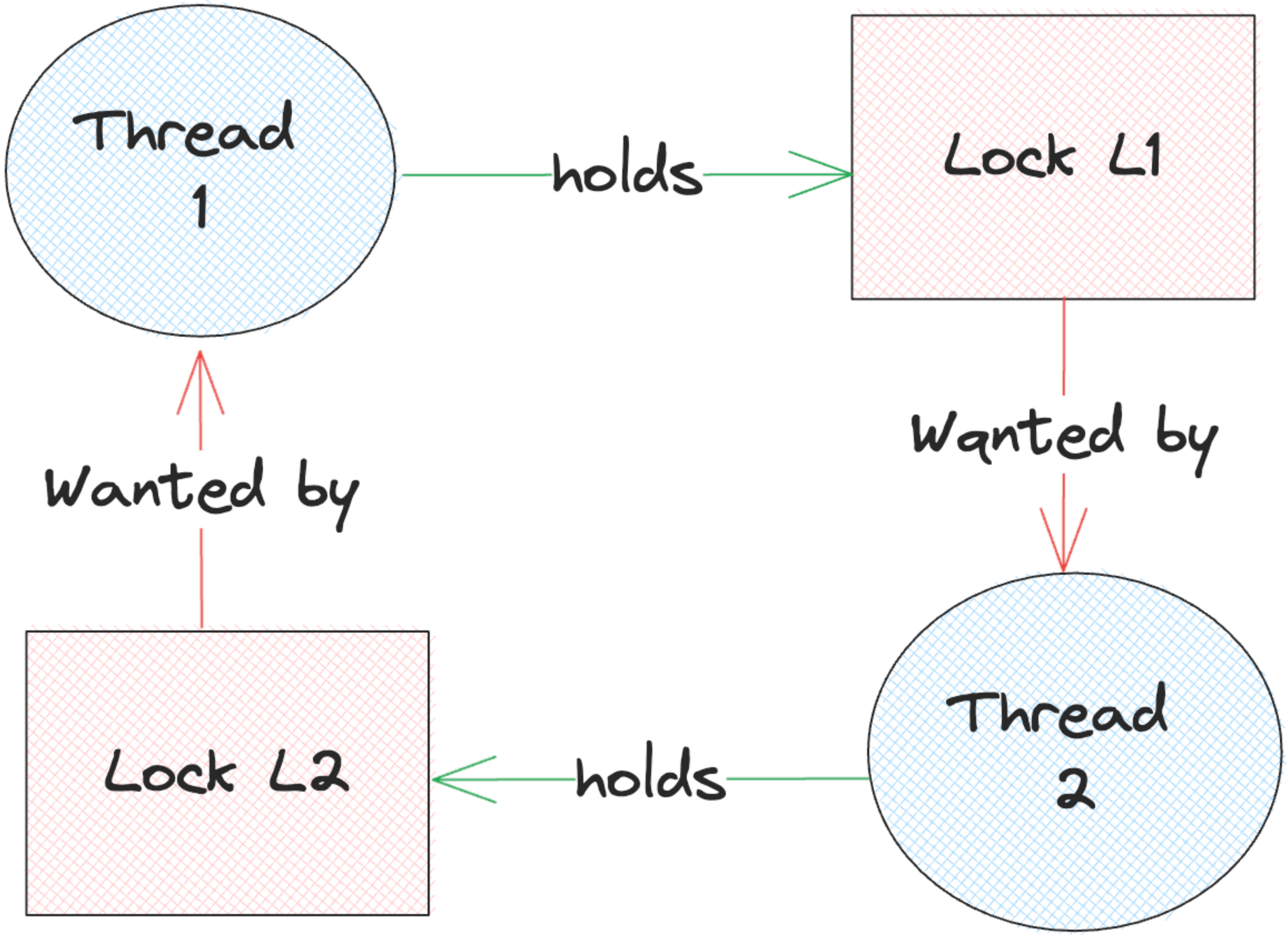
Thread 2

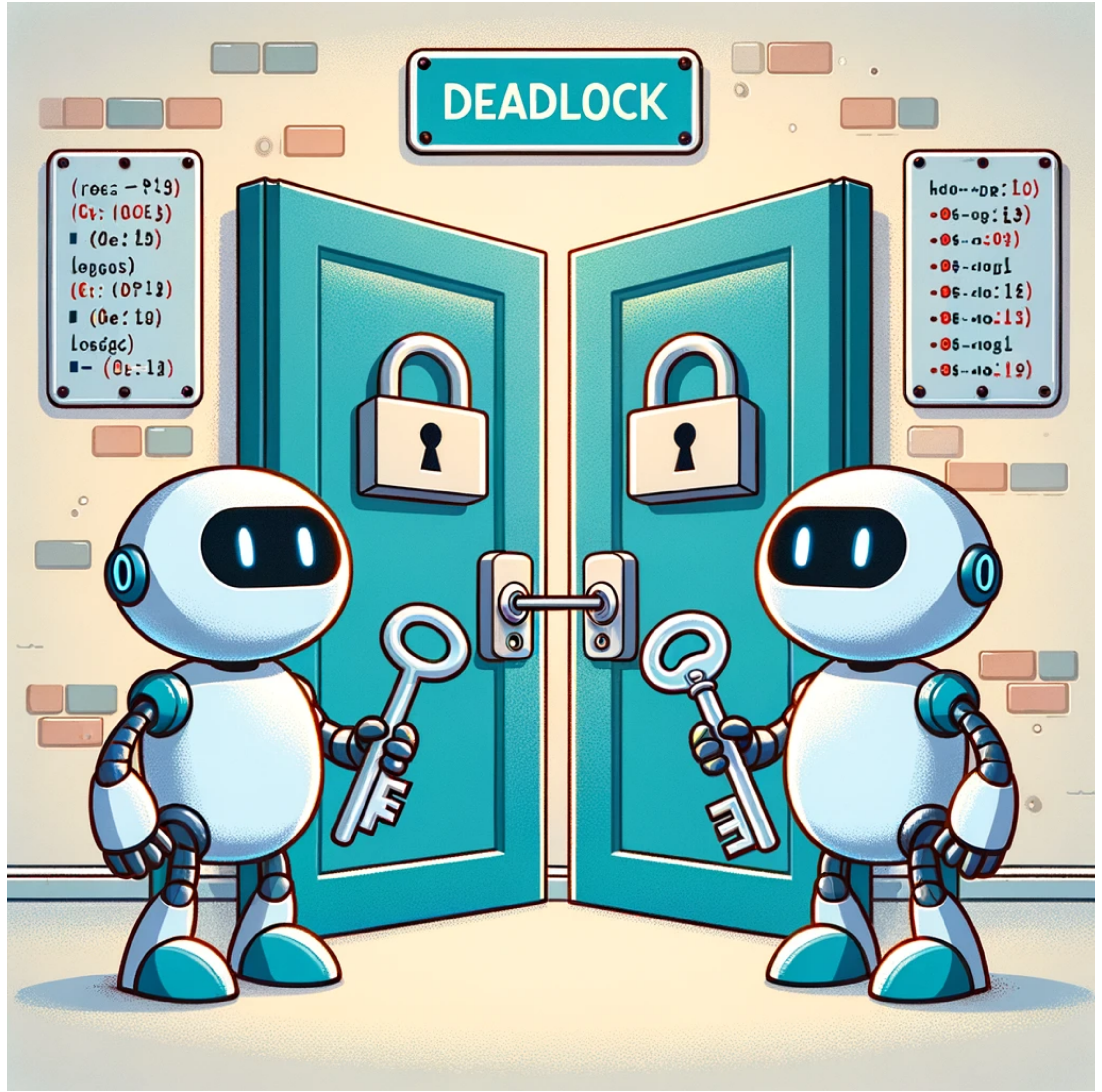
```
pthread_mutex_lock(L2);
pthread_mutex_lock(L1);
```

- Its not always the case that deadlock occurs
- If executions overlap and context switches from thread after acquiring one lock

Deadlock: A Visual Representation

Cycle in a dependency graph





Generated by DALLE-3

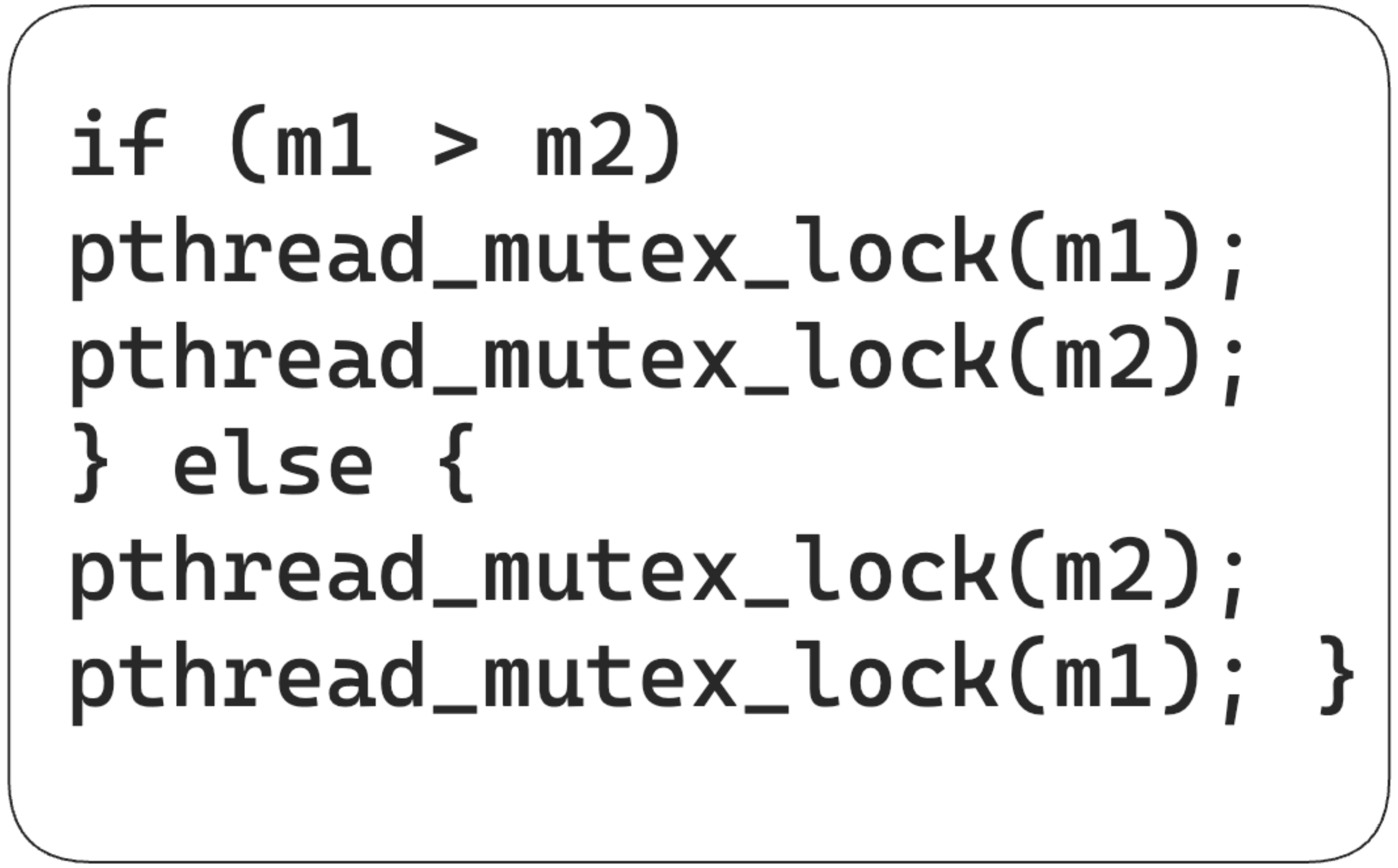
Conditions for deadlock

Four conditions should together hold for deadlock

- **Mutual Exclusion:** Thread claims exclusive control of a resource (eg: lock)
- **Hold-and-wait:** Thread holds a resource and is waiting for another
- **No Preemption:** Thread cannot be made to give up its resource (eg: cannot take back a lock)
- **Circular Wait:** There exists a cycle in the resource dependency graph

Prevention of Circular Wait

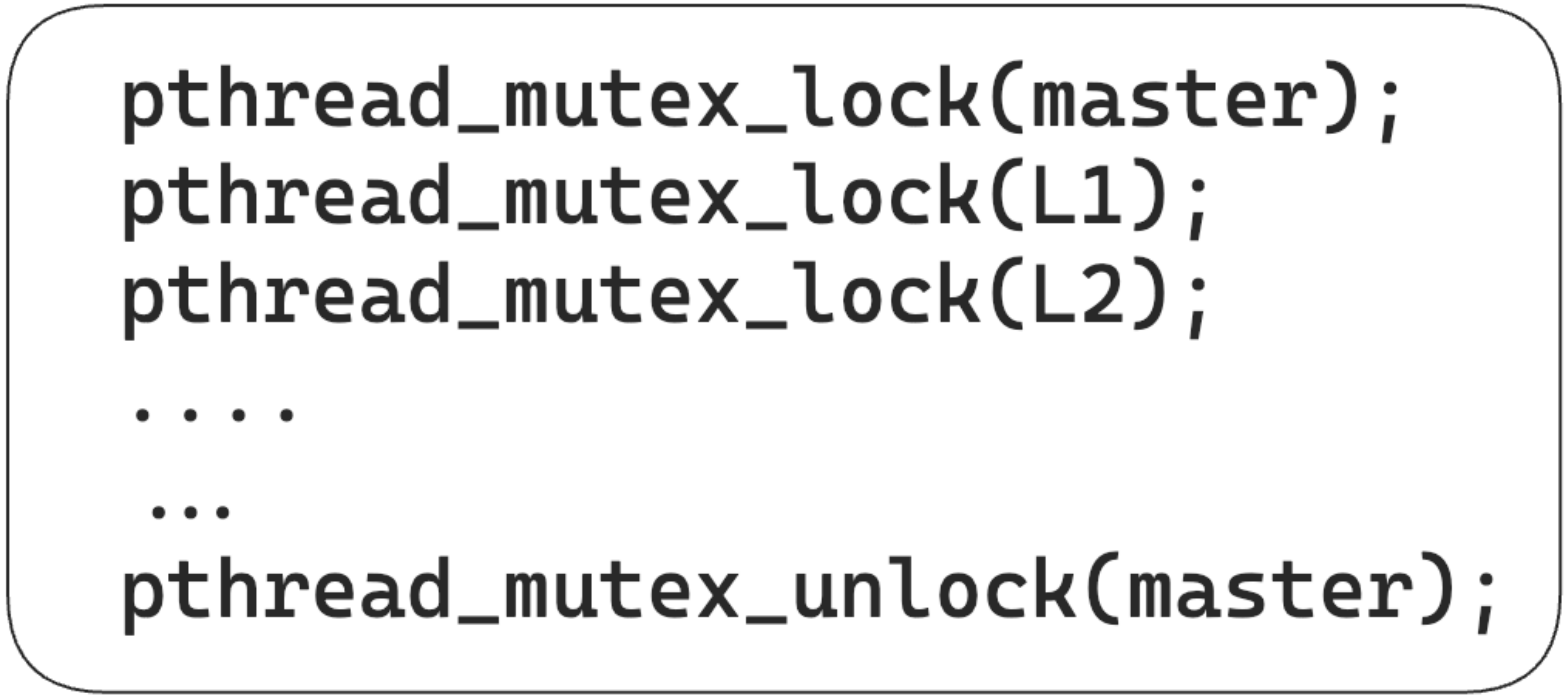
- Acquire locks in a particular order
  - Eg: Thread 1 and thread 2 acquires lock in the same order
- Provide a **total ordering** for lock acquisition
  - If there are only two locks, L1 and L2 => always acquire L1 before L2
- In more complex systems, more than two locks exist => **partial ordering**
  - Some locks can be given higher ordering than other locks
- Lock ordering can also by done using the address of the lock



```
if (m1 > m2)
pthread_mutex_lock(m1);
pthread_mutex_lock(m2);
} else {
pthread_mutex_lock(m2);
pthread_mutex_lock(m1); }
```

Preventing Hold-and-Wait

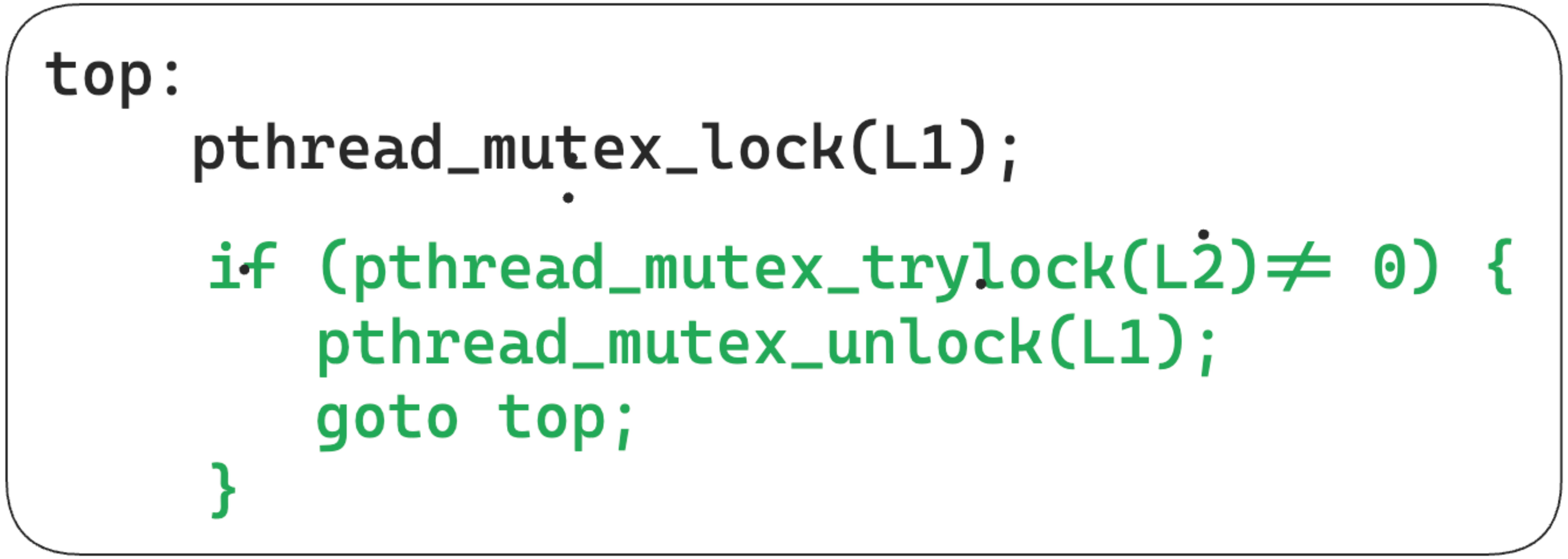
- Hold all the locks at once, atomically by acquiring a master lock first



```
pthread_mutex_lock(master);
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
....
 ...
pthread_mutex_unlock(master);
```

- This may have an impact on concurrent execution and performance gains

“Trying” to get some Preemption Done



```
top:
    pthread_mutex_lock(L1);

     if (pthread_mutex_trylock(L2)≠ 0) {
         pthread_mutex_unlock(L1);
         goto top;
     }
```

- Thread can try for a lock before getting it - **pthread_mutex_trylock**
- Function returns 0 on successfully acquiring the lock
- If other thread also does in same order => **possibility of livelock**
- Periodic delay can be added to avoid live locking

What about avoiding need for mutual exclusion?

- Not using any locks like pthread_locks or condition variables
- Using powerful hardware instructions
  - No need to do explicit locking
  - Hardware primitives like Compare-and-swap can be used
  - For instance, atomic incremental of shared value can be done using 1 line of compare and swap
- No lock, no deadlock but livelock is still a possibility

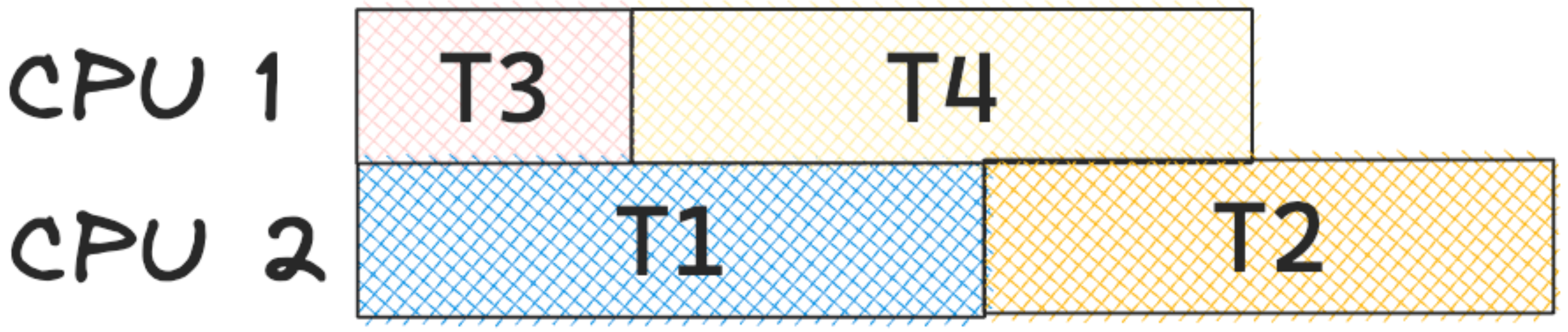
Deadlock Avoidance

- In some scenarios avoidance is preferable instead of prevention

- Deadlock avoidance via **Scheduling**

  - If OS knows which threads requires locks at which point of times, it can schedule them accordingly

	T1	T2	T3	T4
L1	yes	yes	no	no
L2	yes	yes	yes	no



- T1 and T2 are not run at the same time

- T1 and T3 do not share a lock

- Methods like **Bankers algorithm** by Dijkstra have been suggested but practically not applicable

Deadlock Avoidance

Detect and Recover

- Allow deadlocks to occur occasionally and take some action
  - If OS freezes, reboot the system
- Some systems like databases employ deadlock detection and recovery technique
  - Deadlock detector **runs periodically**
  - **Resource graph** is created to detect cycles
  - In the event of cycles, **restart the system**

SCAN ME

Thank you

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