Concurrency: Semaphores

Questions Answered in this Lecture:

- What is a semaphore? Why is it useful? How different from CV?
- How does one implement a lock with a semaphore?
- How to implement producer/consumer with semaphores?
- How to implement reader/writer locks with semaphores?

Thanks to Remzi & Andrea Arapci-Dusseau for slide material

Recall: CV API

- `wait(cond_t * cv, mutex_t * lock)`
  - assumes lock is held when `wait()` is called (***why?***)
  - puts caller to sleep + releases the lock (atomically)
  - when awoken, reacquires lock before returning
- `signal(cond_t * cv)`
  - wake a *single* waiting thread (if >= 1 thread is waiting)
  - if there is no waiting thread, NOP
- `broadcast(cond_t * cv)`
  - wake *all* waiters
  - if no waiting threads, NOP

CV Rules of thumb

- Keep state in addition to CVs
- Always `wait()` or `signal()` ***with lock held***
- Recheck state assumptions when waking up from waiting

[RUNNING]

```
void *producer (void *arg) {
        for (int i = 0; i < loops; i++) {
                mutex_lock(&m); // p1
                while (numfull == max) //p2
                        cond_wait(&cond, &m); //p3
                do_fill(i); // p4
                cond_signal(&cond); // p5
                mutex_unlock(&m); // p6
        }
}
```

[RUNNABLE]

```
void *consumer (void *arg) {
        while (1) {
                mutex_lock(&m); // c1
                while (numfull == 0) // c2
                        cond_wait(&cond, &m);
                int tmp = do_get(); // c4
                cond_signal(&cond); // c5
                mutex_unlock(&m); // c6
                printf("%d\n", tmp); // c7
        }
}
```

wait() wait() signal() wait() signal()

Producer: p1 p2 p3 p4 p5 p6 p1 p2 p3

Consumer1: c1 c2 c3

Consumer2: c1 c2 c3 c2 c4 c5

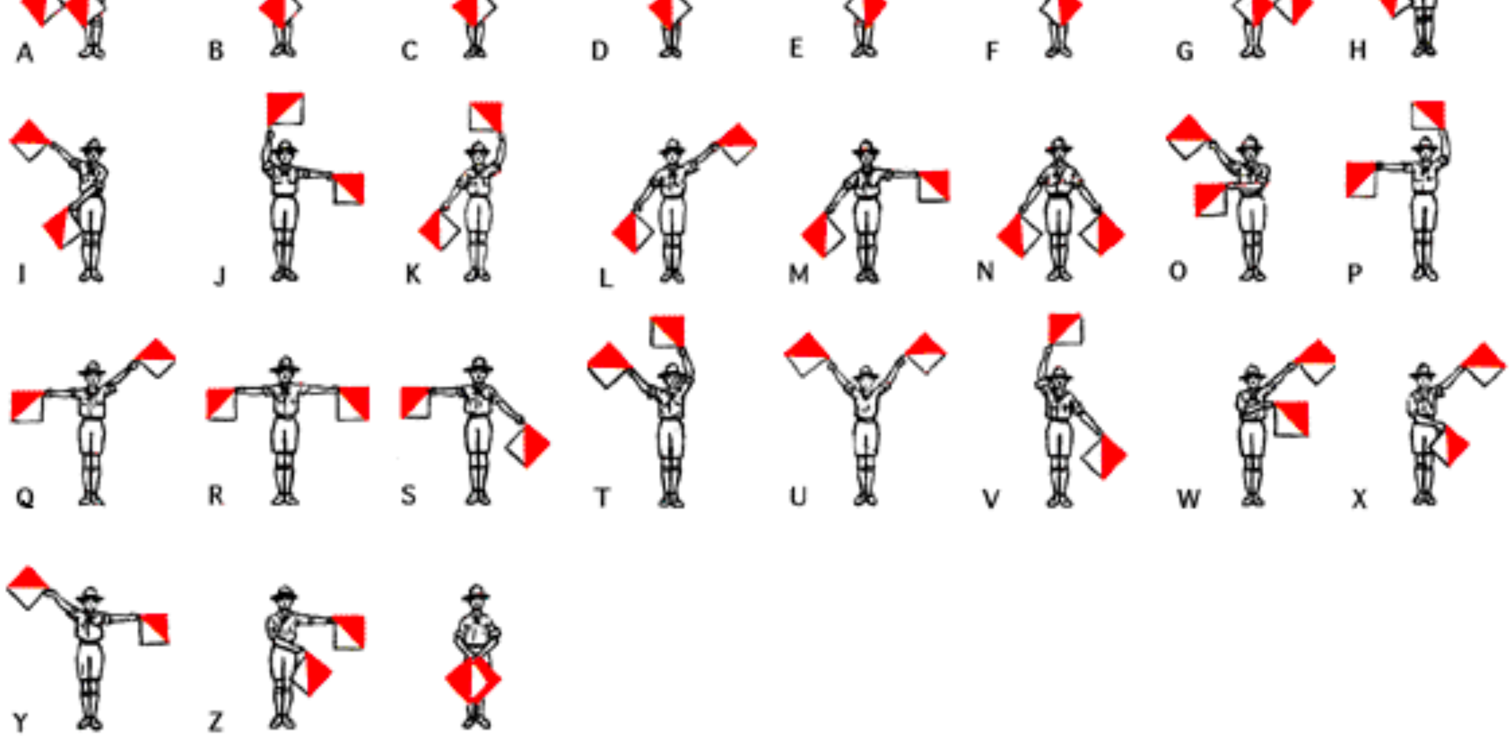
does last signal wake producer or consumer1?

How do we fix this?

- Use 2 CVs! (***one for each logical condition*** that we're signaling)
- Consumers only signal producers
- producers only signal consumers!
- Other option (***covering conditions***) broadcast to everyone!

```c
void *producer (void *arg) {
	for (int i = 0; i < loops; i++) {
		mutex_lock(&m); // p1
		while (numfull == max) //p2
			cond_wait(&empty_cond, &m);
//p3
		do_fill(i); // p4
		cond_signal(&full_cond); // p5
		mutex_unlock(&m); // p6
	}
}
```

```c
void *consumer (void *arg) {
	while (1) {
		mutex_lock(&m); // c1
		while (numfull == 0) // c2
			cond_wait(&full_cond, &m
		int tmp = do_get(); // c4
		cond_signal(&empty_cond); // c5
		mutex_unlock(&m); // c6
		printf("%d\n", tmp); // c7
	}
}
```



Semaphores

What are they?

- Another (earlier) solution to the bounded buffer problem (Dijkstra in the 60s)
- **Ensure mutual** exclusion of a critical section
- **Ensure ordering** among threads in the execution of a concurrent program

Difference between CVs and Semaphores?

- CVs only have a queue. ***State is managed by the programmer!***
- Semaphores include some state (namely, ***a counter***), which is **managed by the implementation**

Semaphores (API)

- `sem_init(sem_t * s, int init_count);`
- `sem_wait(sem_t * s); // decrements count, goes to`
  `// sleep if == -1`
  - sometimes also called p() or down()
- `sem_post(sem_t * s); // increments count, wakes any`
  `//waiters (sleepers)`
  - sometimes also called v() or up()

thread_join()

with locks and CVs

```
void thread_join () {
        mutex_lock(&m);
        if (done == 0)
                cond_wait(&c, &m);
        mutex_unlock(&m);
}
void thread_exit () {
        mutex_lock(&m);
        done = 1;
        cond_signal(&c);
        mutex_unlock(&m);
}
```

with semaphores

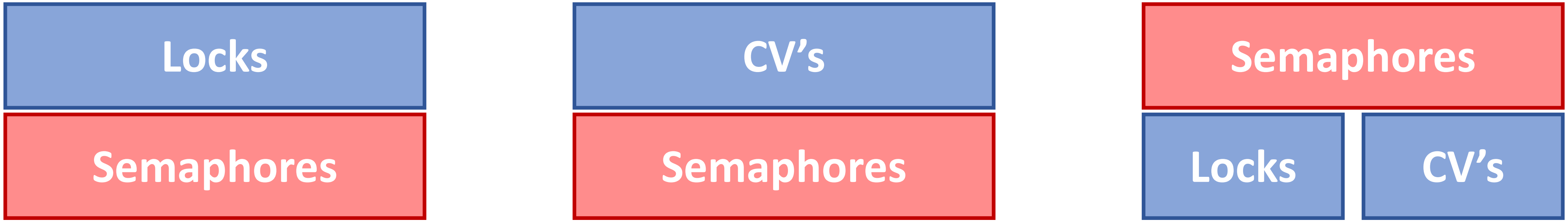
```
sem_t sem;
sem_init(&sem, ???);

void thread_join () {
        sem_wait(&sem);
}
void thread_exit () {
        sem_post(&sem);
}
```

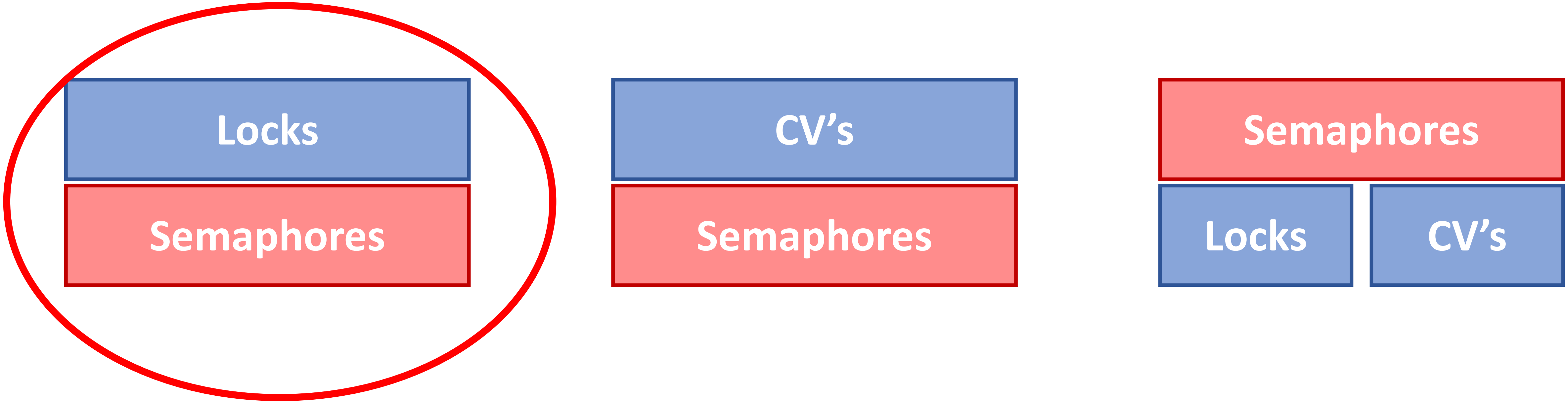
Equivalence

- **Claim**: Semaphores are equally powerful as lock+CVs
- One might be *more convenient* for a particular use case, but that's not the point
- This means ***we can build each out of the other***

Proof outline



Proof outline



```c
typedef struct {

} lock_t;

void init(lock_t *lock) {

}
void acquire(lock_t *lock) {

}
void release(lock_t *lock) {

}
```

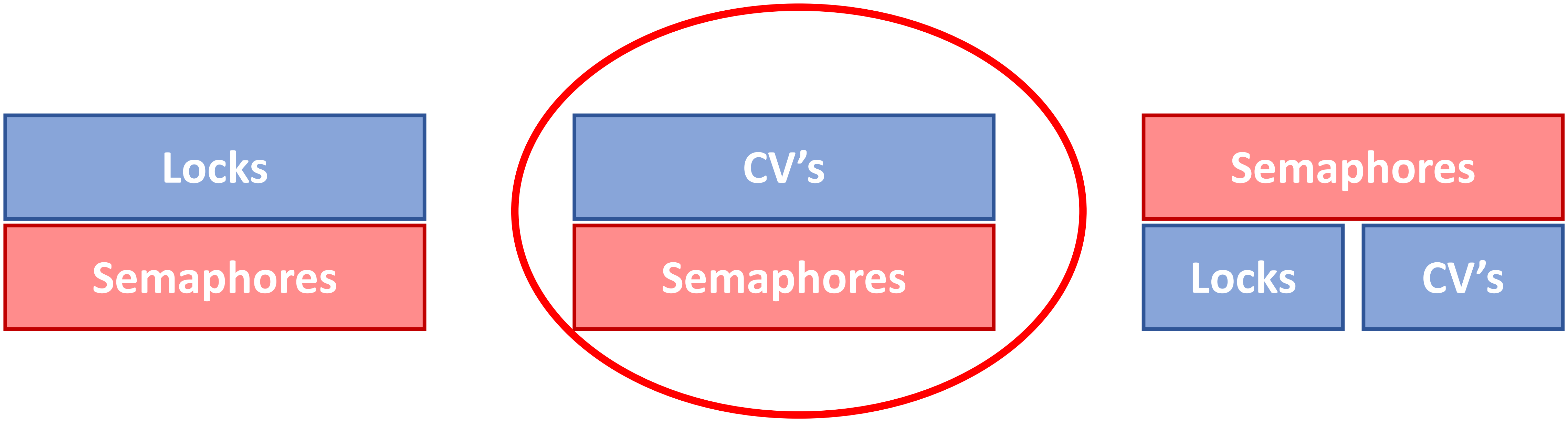
```
typedef struct {
    sem_t sem;
} lock_t;

void init(lock_t *lock) {
    sem_init(&lock->sem, ??);
}
void acquire(lock_t *lock) {
    sem_wait(&lock->sem);
}
void release(lock_t *lock) {
    sem_post(&lock->sem);
}
```

```c
typedef struct {
	sem_t sem;
} lock_t;

void init(lock_t *lock) {
	sem_init(&lock->sem, 1);
}
void acquire(lock_t *lock) {
	sem_wait(&lock->sem);
}
void release(lock_t *lock) {
	sem_post(&lock->sem);
}
```

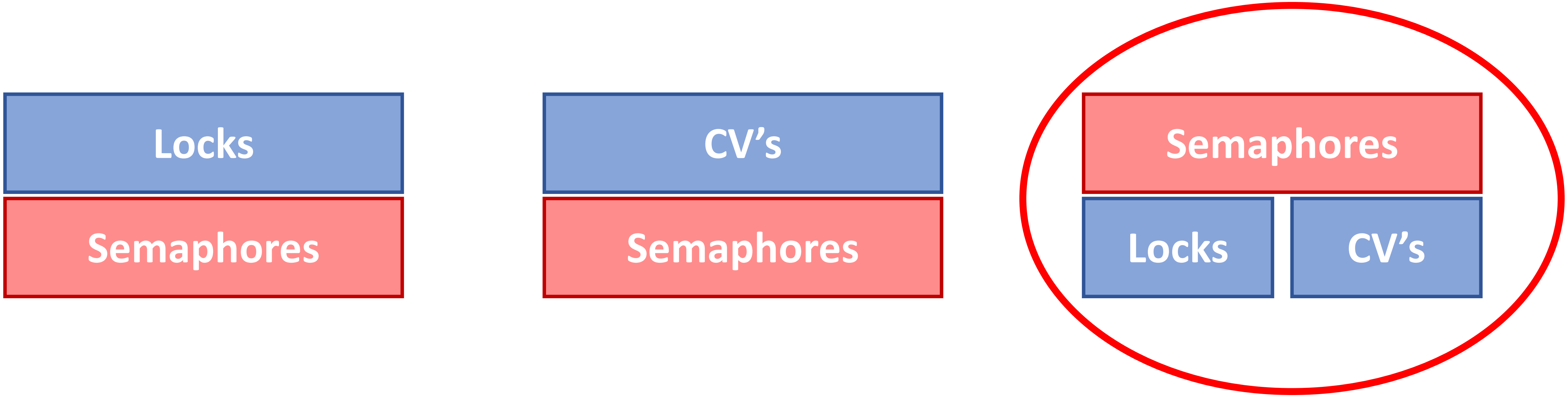
Proof outline



This one is surprisingly subtle

- ***Challenge***: go do it on your own
- Maybe see Andrew Birrell's experience report from Microsoft…

Proof outline



```c
typedef struct {
    // ???
} sem_t;

void sem_init(sem_t *s, int init_count) {
    // ???
}
```

```c
typedef struct {
    int count;
    cond_t cond;
    lock_t lock;
} sem_t;

void sem_init(sem_t *s, int init_count) {
    s->count = init_count;
    cond_init(&s->cond);
    lock_init(&s->lock);
}
```

```c
void sem_wait (sem_t *s) {
    // ???
}
```

```c
void sem_post (sem_t *s) {
    // ???
}
```

```c
void sem_wait (sem_t *s) {
      lock_acquire(&s->lock);
      // atomic stuff
      lock_release(&s->lock);
}
```

```c
void sem_post (sem_t *s) {
      lock_acquire(&s->lock);
      // atomic stuff
      lock_release(&s->lock);
}
```

```c
void sem_wait (sem_t *s) {
     lock_acquire(&s->lock);
     s->count--;
     while (s->count < 0)
          cond_wait(&s->cond);
     lock_release(&s->lock);
}
```

```c
void sem_post (sem_t *s) {
     lock_acquire(&s->lock);
     // atomic stuff
     lock_release(&s->lock);
}
```

```c
void sem_wait (sem_t *s) {
     lock_acquire(&s->lock);
     s->count--;
     while (s->count < 0)
          cond_wait(&s->cond);
     lock_release(&s->lock);
}
```

```c
void sem_post (sem_t *s) {
     lock_acquire(&s->lock);
     s->count++;
     cond_signal(&s->cond);
     lock_release(&s->lock);
}
```

Producer/consumer with semaphores

- Simplest case: one consumer/one producer
- Single shared buffer between them
- **Constraints**:
  - Producer must wait for buffer to be non-full before producing
  - Consumer must wait for buffer to be non-empty before consuming
- ***Use 2 semaphores to get it right***

Producer

```
while (1) {
      sem_wait(&emptyBuffer);
      put(&buffer);
      sem_post(&fullBuffer);
}
```

Consumer

```
while (1) {
      sem_wait(&fullBuffer);
      get(&buffer);
      sem_post(&emptyBuffer);
}
```

What should initial counts be?

Producer/consumer with semaphores

- Simplest case: one consumer/one producer
- Single shared (**circular**) buffer **(with N slots)** between them
- **Constraints**:
  - Producer must wait for buffer to be non-full before producing
  - Consumer must wait for buffer to be non-empty before consuming
- ***Use 2 semaphores to get it right***

Producer

```
i = 0;
while (1) {
      sem_wait(&emptyBuffer);
      put(&buffer[i]);
      i = (i + 1) % N;
      sem_post(&fullBuffer);
}
```

Consumer

```
j = 0;
while (1) {
      sem_wait(&fullBuffer);
      get(&buffer[j]);
      j = (j + 1) % N;
      sem_post(&emptyBuffer);
}
```

What should initial counts be?

MPMC

- General case: **multiple producers/multiple consumers**
- Single shared (**circular**) buffer **(with N slots)** between them
- Share
- **Constraints**:
  - Producer must wait for buffer to be non-full before producing
  - Consumer must wait for buffer to be non-empty before consuming
- ***Use 2 semaphores to get it right***

Producer

```
i = 0;
while (1) {
      sem_wait(&emptyBuffer);
      put(&buffer[i]);
      i = (i + 1) % N;
      sem_post(&fullBuffer);
}
```

Consumer

```
j = 0;
while (1) {
      sem_wait(&fullBuffer);
      get(&buffer[j]);
      j = (j + 1) % N;
      sem_post(&emptyBuffer);
}
```

Will this work?

Producer

```
i = 0;
while (1) {
      sem_wait(&emptyBuffer);
      i = findempty(&buffer);
      put(&buffer[i]);
      sem_post(&fullBuffer);
}
```

Consumer

```
j = 0;
while (1) {
      sem_wait(&fullBuffer);
      j = findfull(&buffer);
      get(&buffer[j]);
      sem_post(&emptyBuffer);
}
```

Producer

What's the problem?

```
i = 0;
while (1) {
	sem_wait(&mutex);
	sem_wait(&emptyBuffer);
	i = findempty(&buffer);
	put(&buffer[i]);
	sem_post(&fullBuffer);
	sem_post(&mutex);
}
```

Consumer

```
j = 0;
while (1) {
	sem_wait(&mutex);
	sem_wait(&fullBuffer);
	j = findfull(&buffer);
	get(&buffer[j]);
	sem_post(&emptyBuffer);
	sem_post(&mutex);
}
```

Producer **Works, but limits concurrency** **Consumer**

```
i = 0;
while (1) {
      sem_wait(&emptyBuffer);
      sem_wait(&mutex);
      i = findempty(&buffer);
      put(&buffer[i]);
      sem_post(&mutex);
      sem_post(&fullBuffer);
}
```

```
j = 0;
while (1) {
      sem_wait(&fullBuffer);
      sem_wait(&mutex);
      j = findfull(&buffer);
      get(&buffer[j]);
      sem_post(&mutex);
      sem_post(&emptyBuffer);
}
```

Increases concurrency (in producing/consuming)

Producer

```
i = 0;
while (1) {
      sem_wait(&emptyBuffer);
      sem_wait(&mutex);
      i = findempty(&buffer);
      sem_post(&mutex);
      put(&buffer[i]);
      sem_post(&fullBuffer);
}
```

Consumer

```
j = 0;
while (1) {
      sem_wait(&fullBuffer);
      sem_wait(&mutex);
      j = findfull(&buffer);
      sem_post(&mutex);
      get(&buffer[j]);
      sem_post(&emptyBuffer);
}
```

Reader Writer Locks

- Operations on shared data are ***not symmetric***
- If many threads attempt to read a lock:
  - Normal locks will prevent this
  - **But**, if there **no changes to the state**, why shouldn't they be able to?
- So writers (changers of state) should be treated differently from readers

A Conceptual Solution

- As long as there are no writers, readers can proceed concurrently
- Writers must wait for readers to drain
- Readers must wait for writers to finish (**writers have exclusive access**)

Reader/writer locks

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

Reader/writer locks

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

Reader/writer locks

```
void rw_readlock (rwlock_t *l) {
      sem_wait(&l->lock); // grab read lock
      l->readers++;     // this is the critical section
      if (readers == 1) // since there are readers, writer must wait
            sem_wait(&l->writelock);
      sem_post(&l->lock); // other readers can continue
}
```

Reader/writer locks

```
void rw_readunlock (rwlock_t *l) {
      sem_wait(&l->lock); // grab read lock
      l->readers--;       // this is the critical section
      if (readers == 0) // no more readers, writers can cont.
            sem_post(&l->writelock);
      sem_post(&l->lock); // other readers can continue
}
```

Reader/writer locks

```
void rw_writelock (rwlock_t *l) {
     sem_wait(&l->writelock); // grab write lock
     // only continues if there are no readers!
}

void rw_writeunlock (rwlock_t *l) {
     sem_post(&l->writelock); // release write lock
}
```

Stepping back

- We've considered mechanisms for ***mutual exclusion*** and ***ordering*** of events
- Mostly we've talked about them in the context of ***threads executing concurrently***
- Is this more broadly applicable? **Hint**: is the universe concurrent?
- E.g.
  - What if two base stations are trying to send a firmware update to Mars rover at the same time?
    - How do we ensure atomicity?
    - What does spinning/waiting look like?
- Put another way, **how do we ensure *mutual exclusion* and *ordering* for a distributed system**? (answered in CS550)