Concurrency: Signaling and Condition Variables

Questions Answered in this Lecture:

- How do we make fair locks perform better?
- How do we notify threads of that some condition has been met?

Recall: Ticket Lock Implementation

```
typedef struct __lock_t {
        int ticket;
        int turn;
}

void lock_init(lock_t *lock)
{
        lock->ticket = 0;
        lock->turn   = 0;
}
```

```
void acquire(lock_t *lock) {
        int myturn = FAA(&lock->ticket);
        while (lock->turn != myturn); // spin
}

void release (lock_t *lock) {
        FAA(&lock->turn);
}
```

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Spinlock Performance

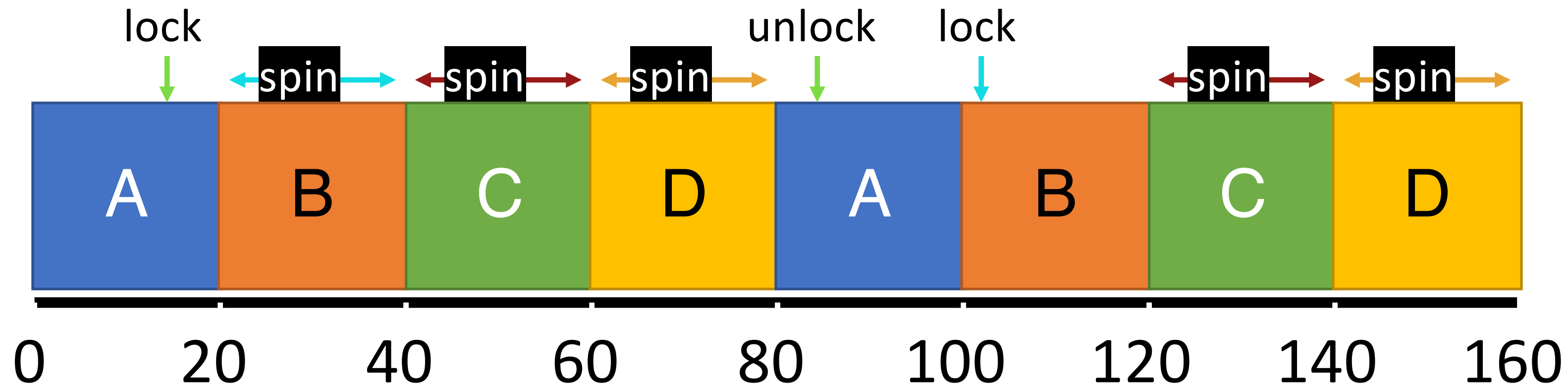
Fast when…

- many CPUs
- locks held a short time
- advantage: avoid context switch

Slow when…

- one CPU
- locks held a long time
- disadvantage: spinning is wasteful

CPU Scheduler is Ignorant



CPU scheduler may run **B** instead of **A**
even though **B** is waiting for **A**

Ticket Lock with `yield()`

```
typedef struct __lock_t {
        int ticket;
        int turn;
}

void lock_init(lock_t *lock)
{
        lock->ticket = 0;
        lock->turn = 0;
}
```

```
void acquire(lock_t *lock) {
        int myturn = FAA(&lock->ticket);
        while (lock->turn != myturn)
                yield();
}

void release (lock_t *lock) {
        FAA(&lock->turn);
}
```

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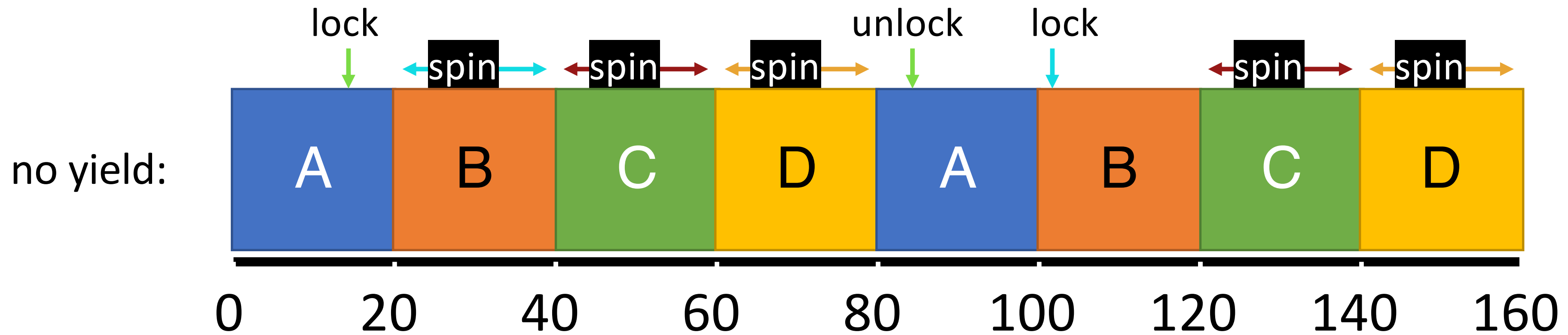
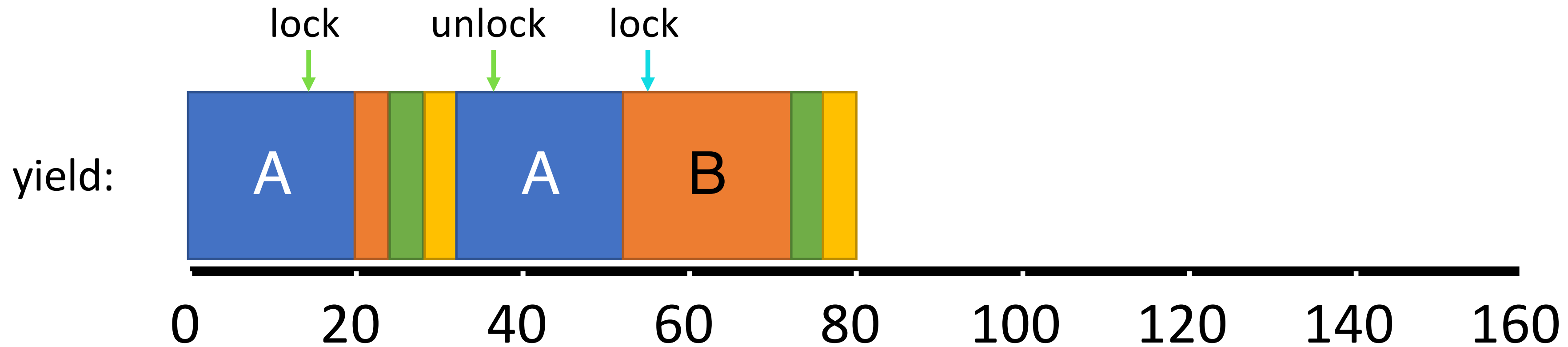
`yield()` Instead of spin





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Spinlock Performance

Waste…

Without yield: O(threads * **time_slice**)

With yield: O(threads * **context_switch**)

So even with yield, spinning is slow with high thread contention

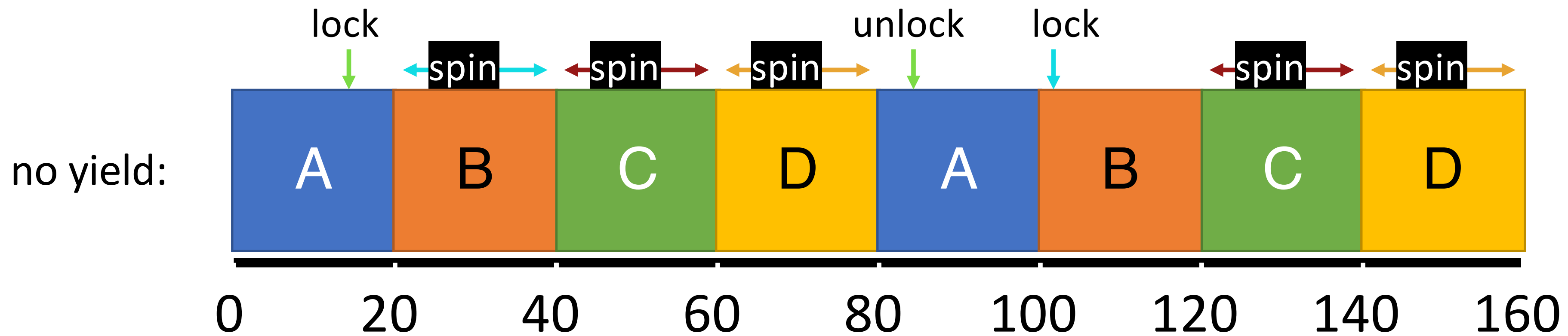
Next improvement: Block and put thread on waiting queue instead of spinning

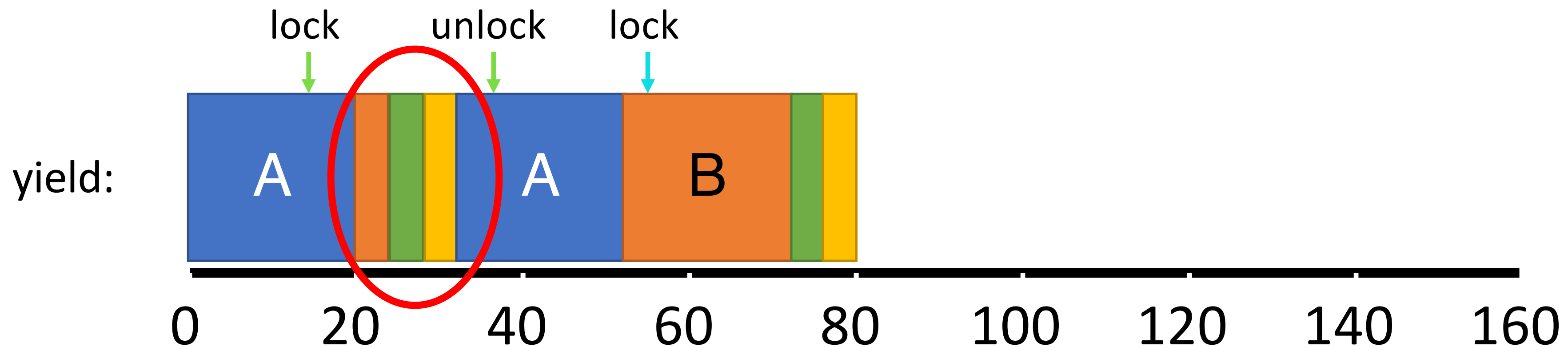
How do we evaluate lock performance?

- **Fairness**:
  - do some processes wait more than others?
  - another way: do processes get lock in order requested?
- **Performance**: it depends…
  - Is the lock ***contended?*** (many threads attempting to acquire lock)
  - Or is it ***uncontended?*** (likely to get the lock if we request it)

Why is `yield()` useful?

How can it affect performance?





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Lock implementation: block when waiting

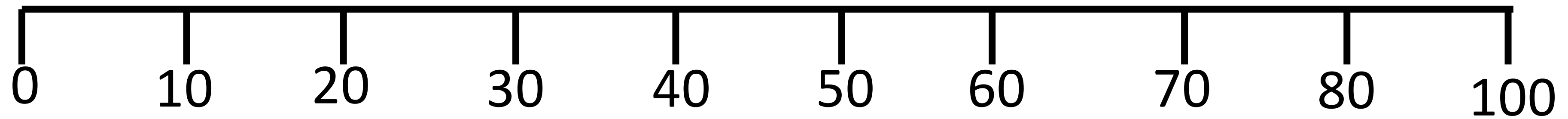
- Lock ***implementation*** removes waiting threads from the ready queue (e.g. with `park()` and `unpark()`)
- Scheduler only runs **ready** threads
- ***Separates concerns*** (programmer doesn't need to deal with yield vs not/spinning issue)
- **Quiz**: where should locks be implemented?

Example

Ready: {A, B, C, D}

Waiting: {}

Running: {}

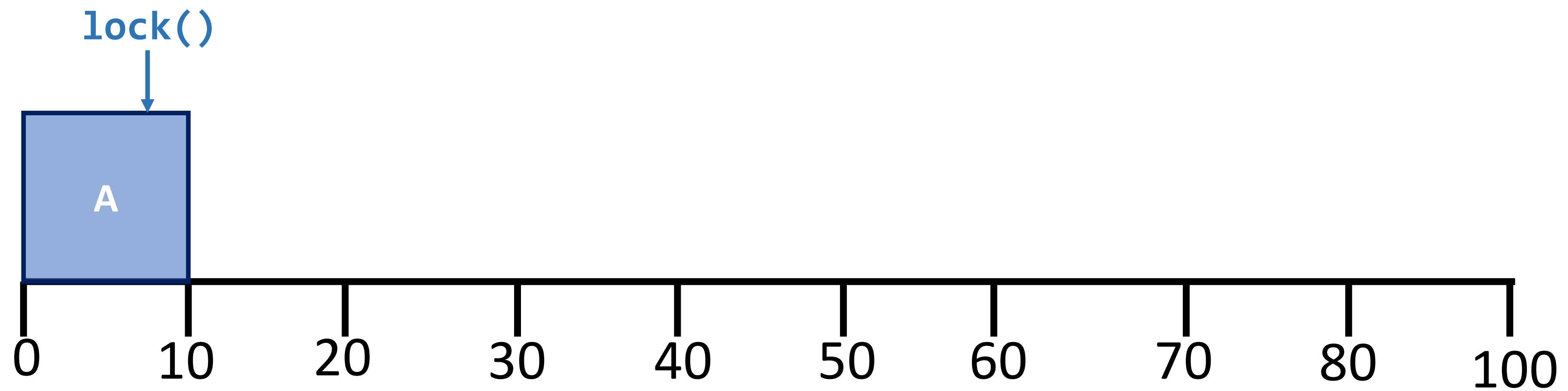


Example

Ready: {B, C, D}

Waiting: {}

Running: {A}

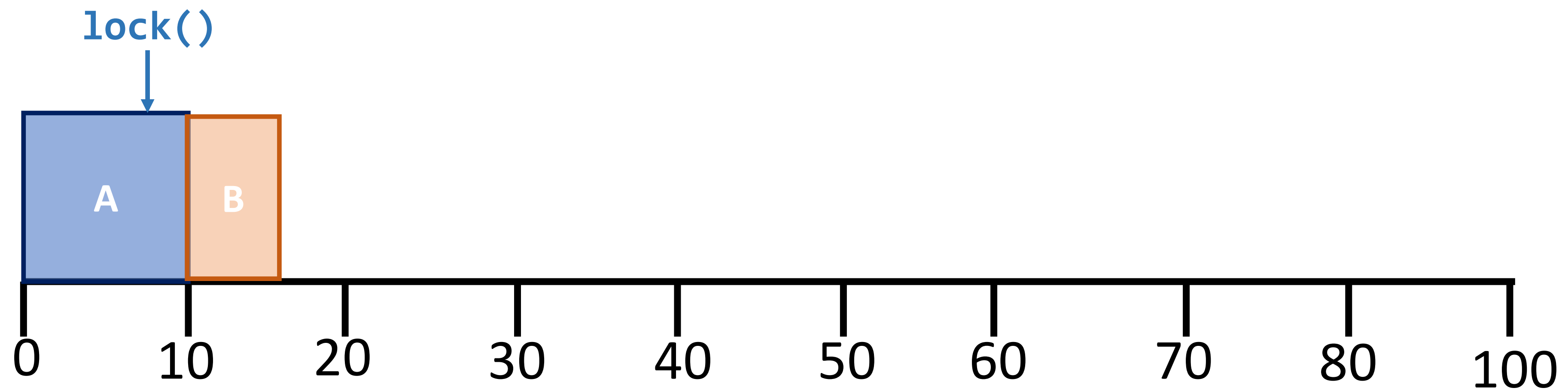


Example

Ready: {A, C, D}

Waiting: {}

Running: {B}

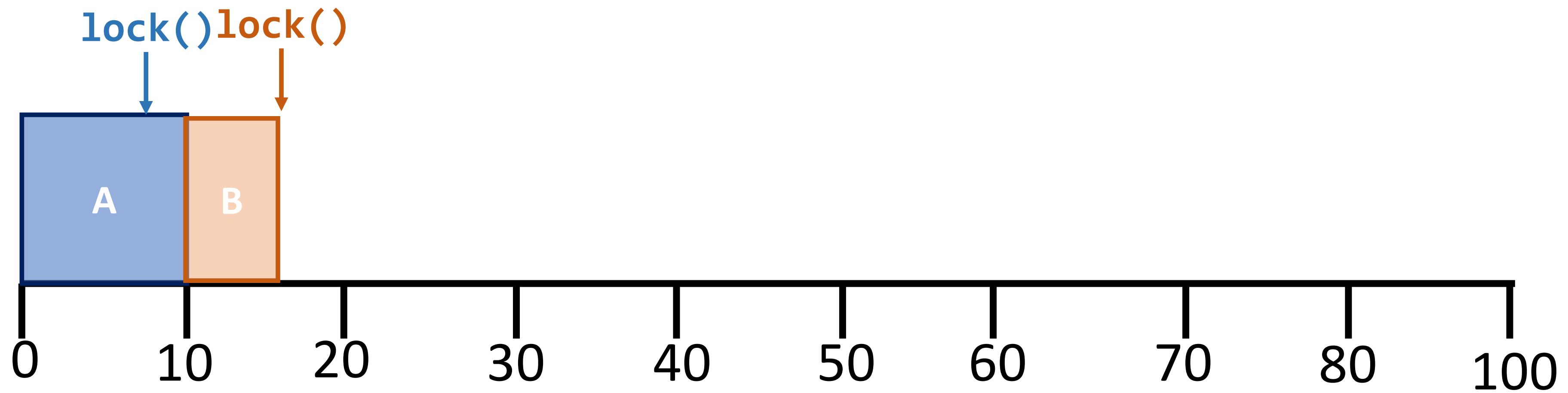


Example

Ready: {A, C, D}

Waiting: {B}

Running: {}

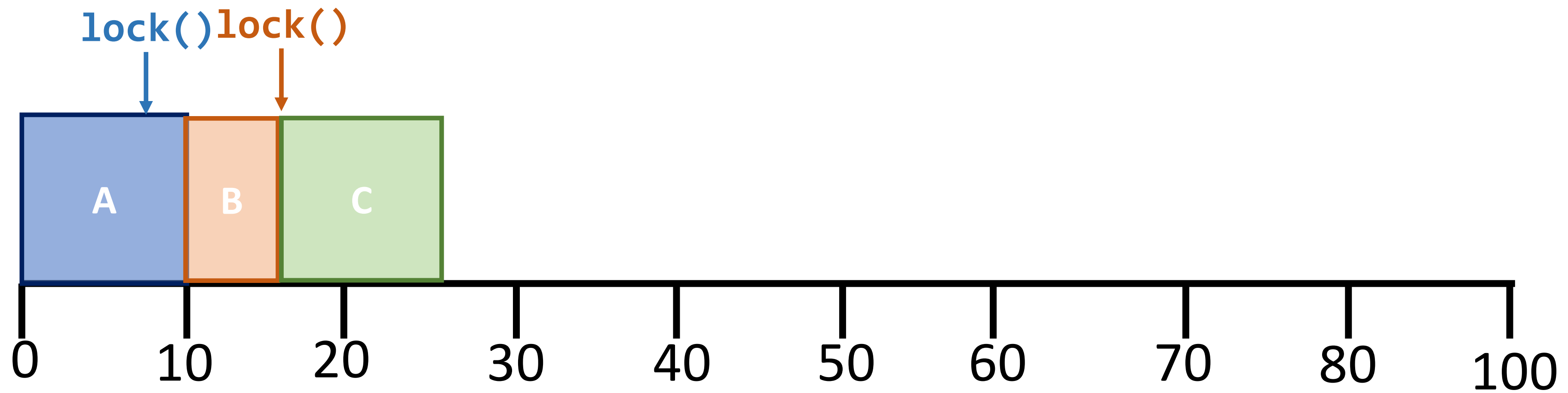


Example

Ready: {A, D}

Waiting: {B}

Running: {C}

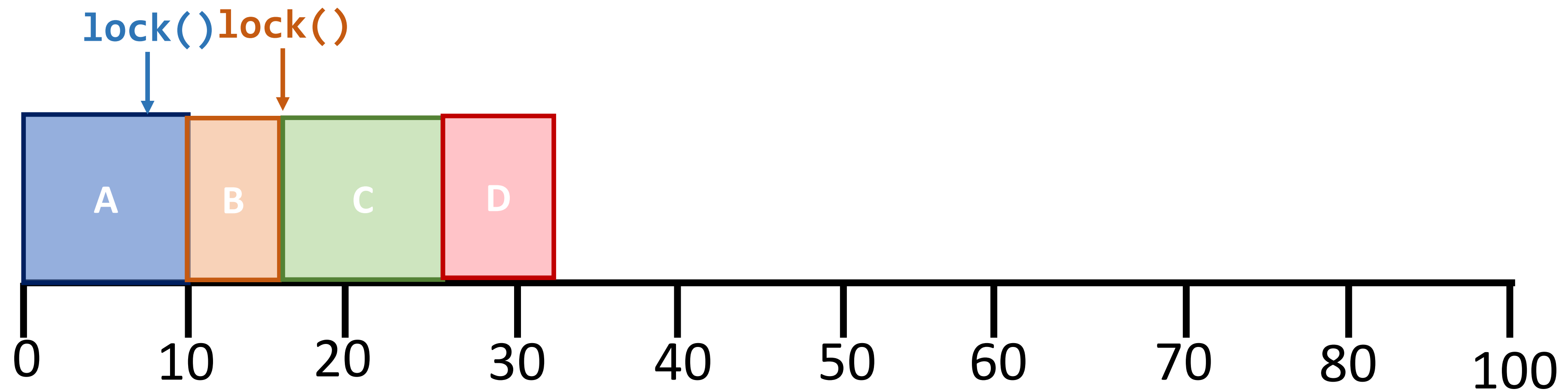


Example

Ready: {A, C}

Waiting: {B}

Running: {D}

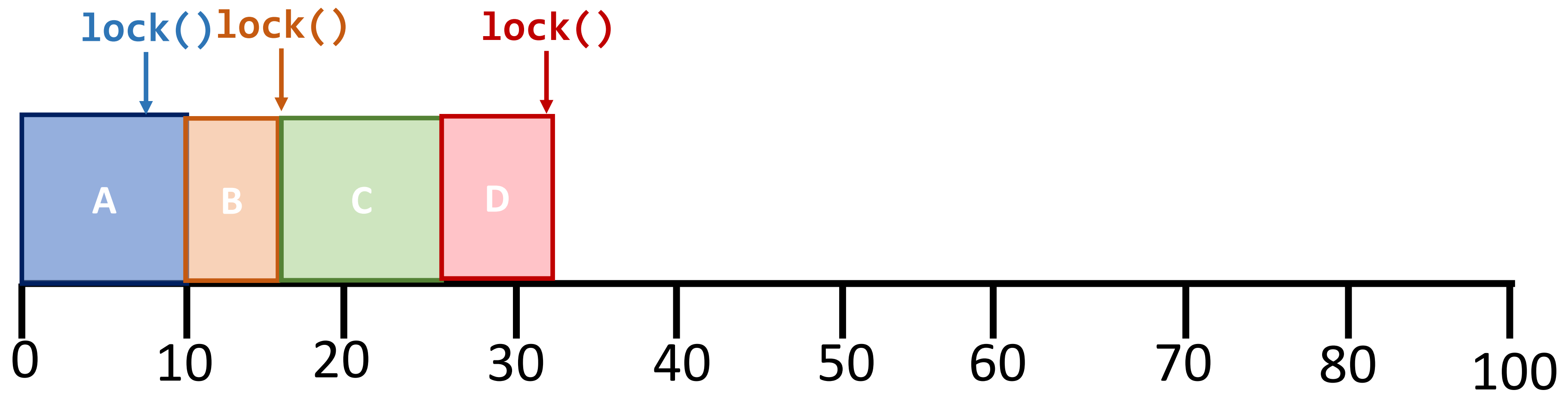


Example

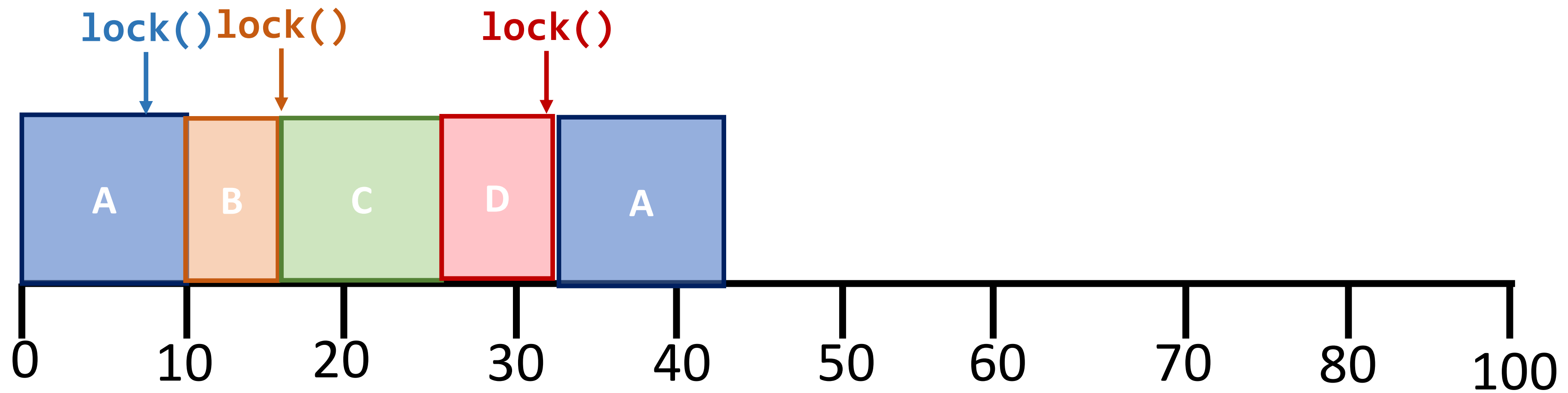
Ready: {A, C}

Waiting: {B, D}

Running: {}



Example

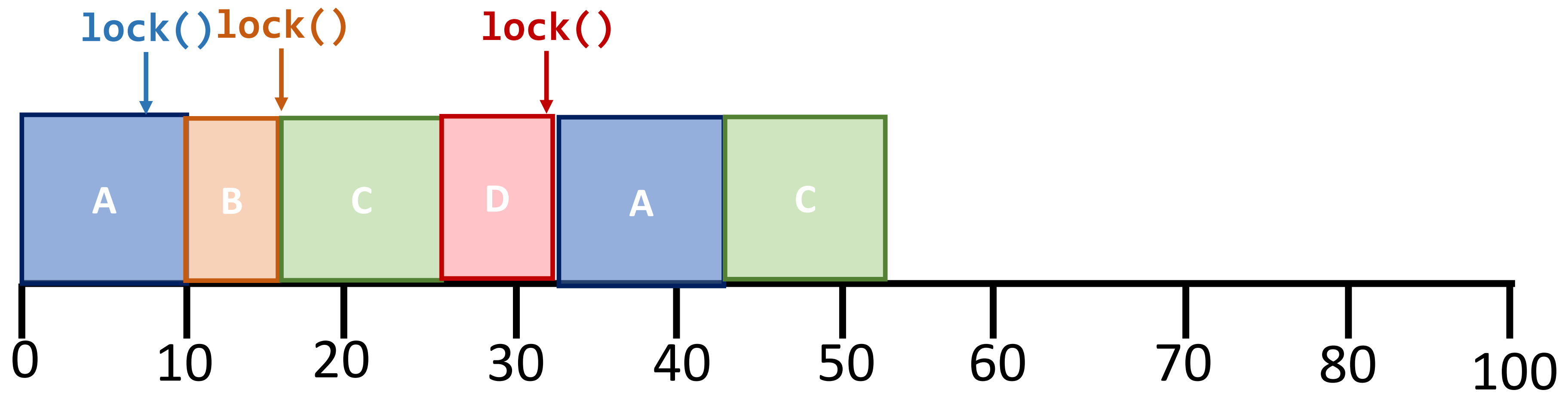


Example

Ready: {A}

Waiting: {B, D}

Running: {C}

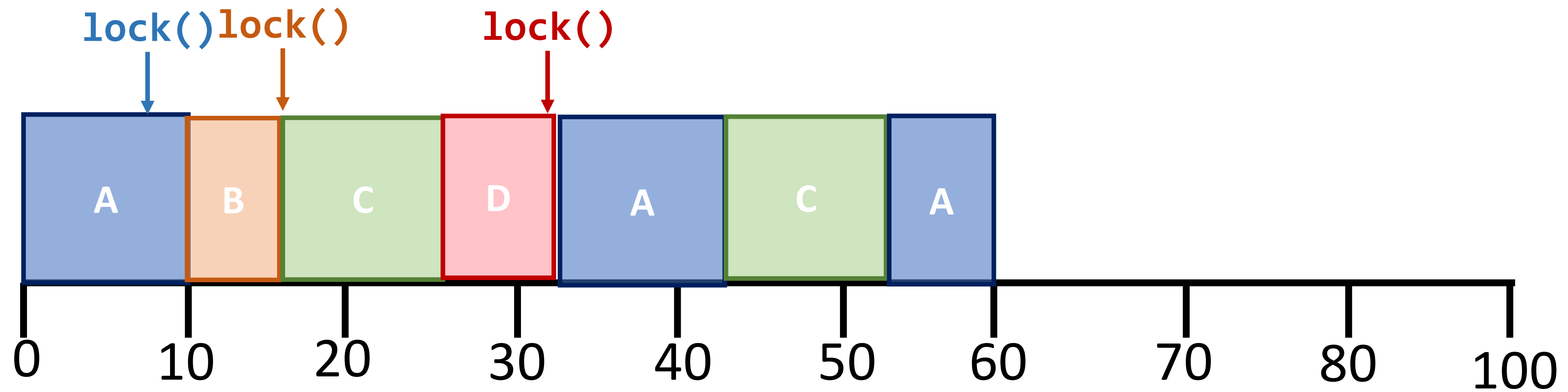


Example

Ready: {C}

Waiting: {B, D}

Running: {A}

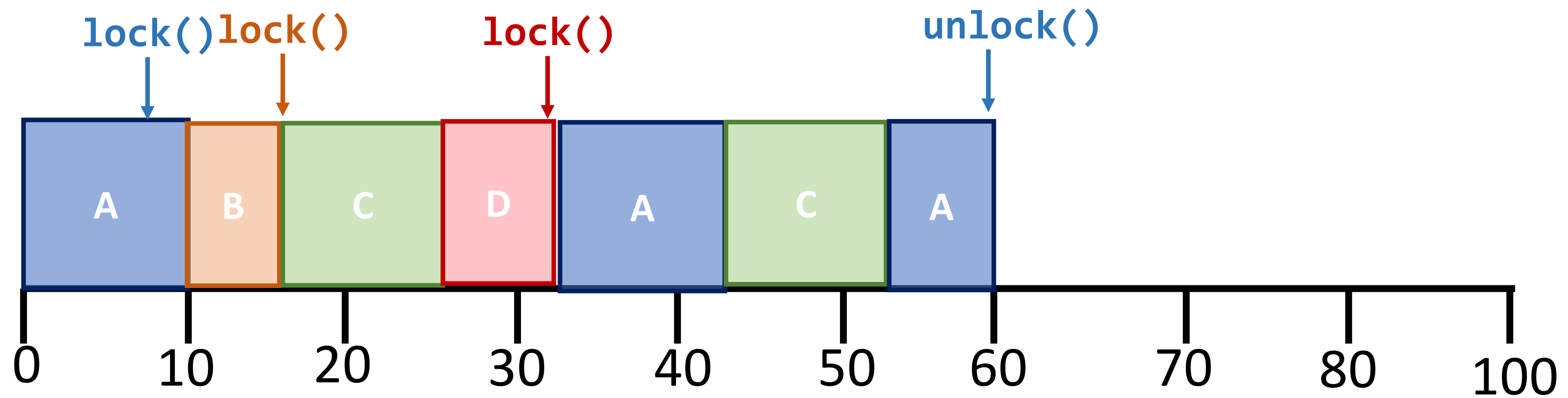


Example

Ready: {C, B, D}

Waiting: {}

Running: {A}

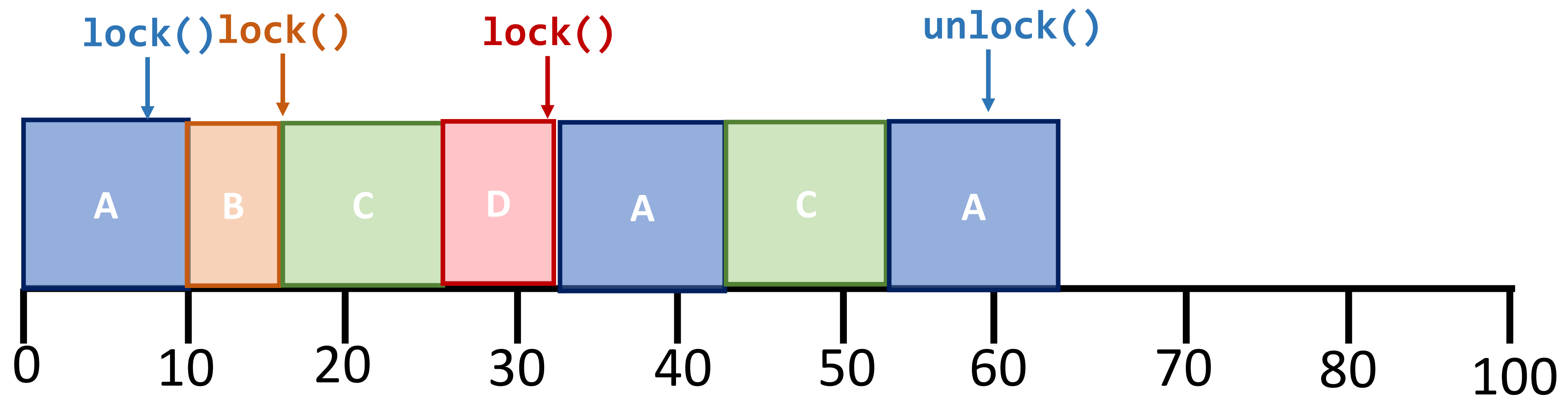


Example

Ready: {C, B, D}

Waiting: {}

Running: {A}

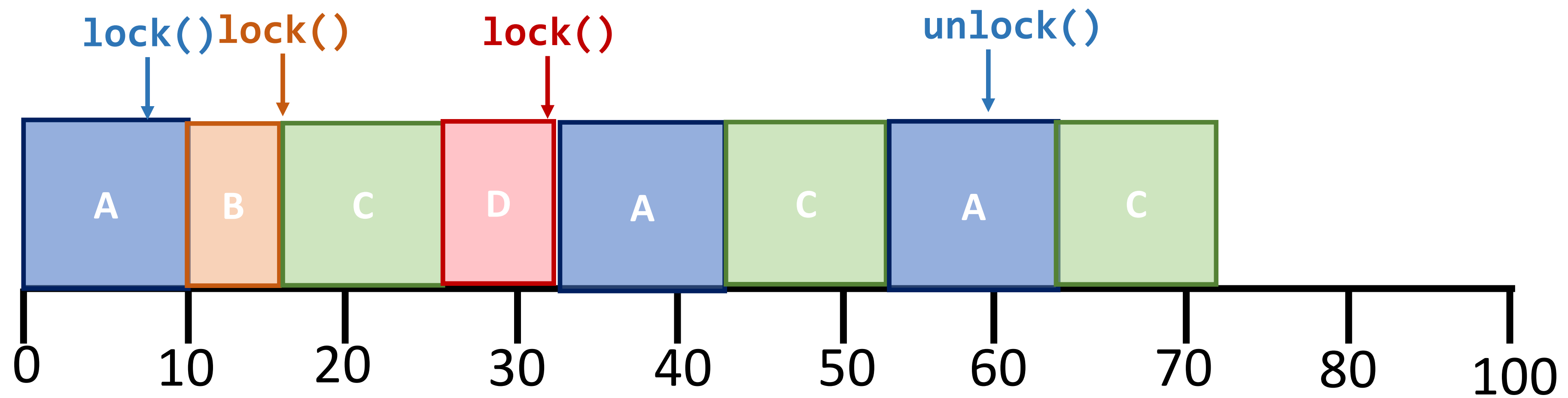


Example

Ready: {B, D, A}

Waiting: {}

Running: {C}

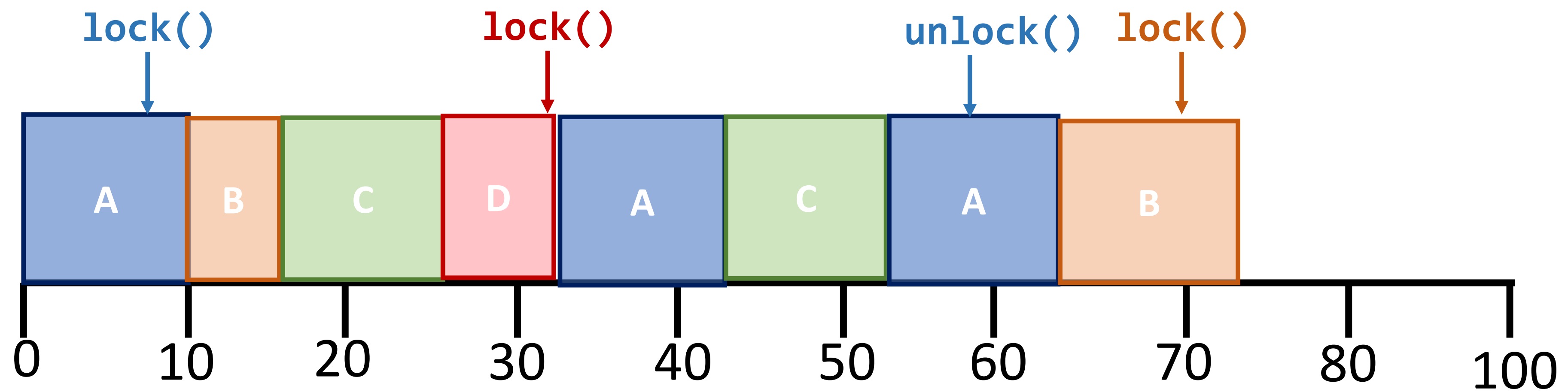


Example

Ready: {D, A, C}

Waiting: {}

Running: {B}



What do we get?

- ***Threads aren't contending on the lock*** when they shouldn't be (mostly)
- **Fewer context switches**

Lock: block when waiting

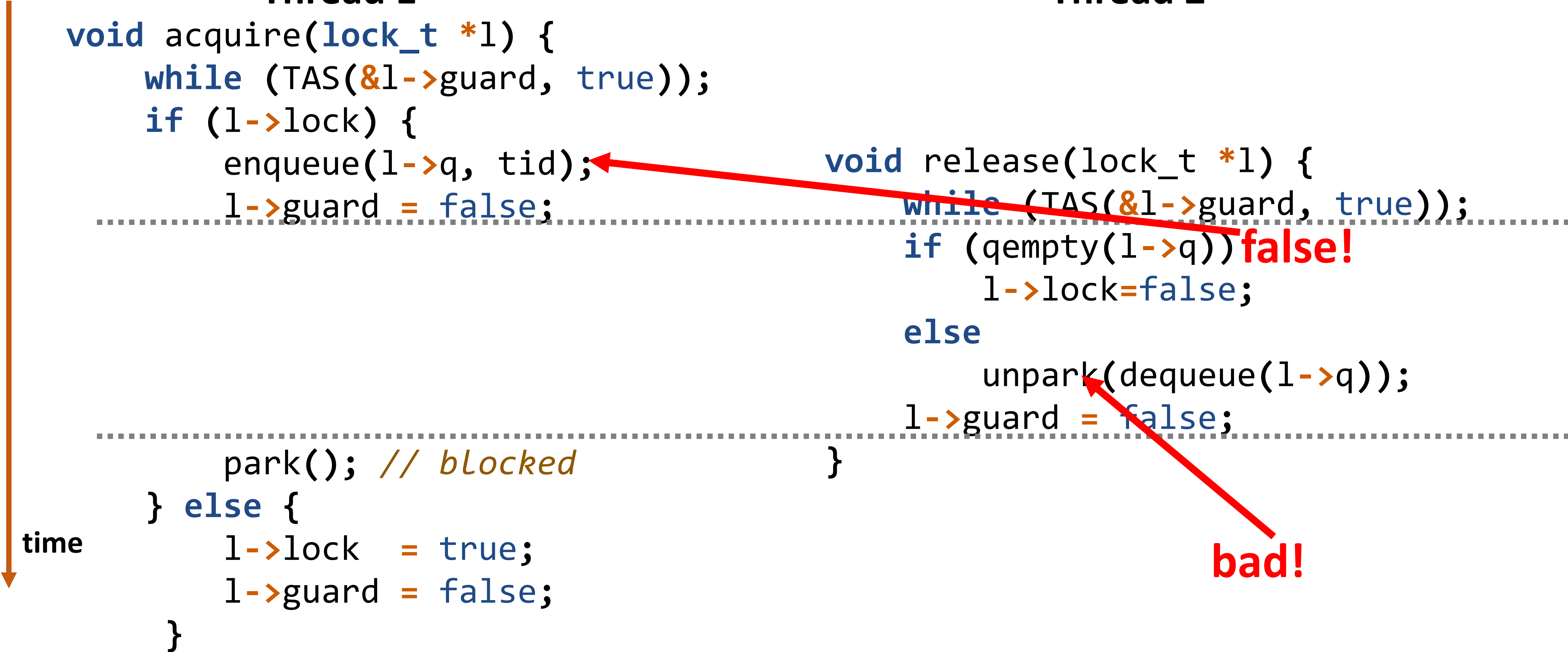
```
typedef struct {
    bool lock  = false;
    bool guard = false;
    queue_t q;
} lock_t;
```

1. Why do we need guard?
2. Why is it OK to spin on guard?
3. In `release()`, why not set `lock=false`?
4. What is the race condition?

```
void acquire(lock_t *l) {
    while (TAS(&l->guard, true));
    if (l->lock) {
        enqueue(l->q, tid);
        l->guard = false;
        park(); // blocked
    } else {
        l->lock  = true;
        l->guard = false;
    }
}

void release(lock_t *l) {
    while (TAS(&l->guard, true));
    if (qempty(l->q))
        l->lock=false;
    else
        unpark(dequeue(l->q));
    l->guard = false;
}
```

Race!



Lock: the fix

```
typedef struct {
    bool lock  = false;
    bool guard = false;
    queue_t q;
} lock_t;
```

1. **Why does this fix the race?**
2. **What does the scheduler need to do here?**
3. **Why can’t we just hold the guard when we park()?**

```
void acquire(lock_t *l) {
    while (TAS(&l->guard, true));
    if (l->lock) {
        enqueue(l->q, tid);
        setpark(); // notify of plan
        l->guard = false;
        park(); // unless unpark()
    } else {
        l->lock  = true;
        l->guard = false;
    }
}
void release(lock_t *l) {
    while (TAS(&l->guard, true));
    if (qempty(l->q))
        l->lock=false;
    else
        unpark(dequeue(l->q));
    l->guard = false;
}
```

Spin-waiting vs. Blocking

- Each approach has ***tradeoffs***:
- **Uniprocessor**
  - Waiting process is scheduled -> process holding lock isn't
  - Waiting process should always be descheduled
  - Associate queue of waiters with each lock
- **Multiprocessor**
  - Waiting process is scheduled -> **process holding lock might also be**
  - Spin or block depends on **how long (*t*) before lock is released**
  - Lock released quickly? `spin()`
  - Lock taken for long time? `block()`

we'll define this relative to the context switch time

Oracle

- Suppose we know how long **(t)** a lock will be held
- And suppose **we make our decision to block or spin based on C, the cost of a context switch**

$$action = \begin{cases} t \leq C & \rightarrow spin \\ t > C & \rightarrow block \end{cases}$$

BUT: we have to know the future!

Applying Bounds

- The theory: **bound our worst-case performance using actual wait time over optimal** (oracle)
- Consider:

$t \leq C$

What would the oracle do?

What can we do (without knowing future)?

$t > C$

What would the oracle do?

What can we do?

We pay 2C, because we wait an extra C. 2C/C = 2 => 2-competitive algorithm!

Concurrency Goals

- **Mutual Exclusion**
  - Keep two threads from executing in a critical section concurrently
  - We solved this with ***locks***
- **Dependent Events**
  - We want a thread to wait until some particular event has occurred
  - Or some condition has been met
  - Solved with ***condition variables*** and ***semaphores***

“I just dropped in to see what condition my condition was in”

Example: join()

```
pthread_t p1, p2;
pthread_create(&p1, NULL, mythread, “A”);
pthread_create(&p2, NULL, mythread, “B”);
// join waits for the threads to finish
pthread_join(p1, NULL);
pthread_join(p2, NULL);
printf(“Main: done\n [balance: %d]\n”, balance);
return 0;
```

Condition Variables

- **CV**: queue of waiting threads
- **B** waits for a signal on CV before running
  - `wait(CV, …);`
- **A** sends signal() on CV when time for **B** to run
  - `signal(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

Join Implementation: Attempt #1

parent

```
void thread_join() {
    mutex_lock(&m);     // x
    cond_wait(&c, &m); // y
    mutex_unlock(&m);  // z
}
```

child

```
void thread_exit() {
    mutex_lock(&m);      // a
    cond_signal(&c);     // b
    mutex_unlock(&m);    // c
}
```

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Join Implementation: Attempt #1

parent

```
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        mutex_lock(&m);       // x
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child

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void thread_exit() {
        mutex_lock(&m);         // a
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        mutex_unlock(&m);       // c
}
```

Example schedule:

parent x y z

child a b c

Join Implementation: Attempt #1

parent

```
void thread_join() {
    mutex_lock(&m);     // x
    cond_wait(&c, &m); // y
    mutex_unlock(&m);  // z
}
```

child

```
void thread_exit() {
    mutex_lock(&m);      // a
    cond_signal(&c);     // b
    mutex_unlock(&m);    // c
}
```

Example (bad) schedule:

parent x y

child a b c

parent will wait forever!

Rule of Thumb #1

- ***Always associate some state*** with the CV
- CVs are used to `signal()` when state ***changes***
- If state is as required, ***don’t need to wait*** for a `signal()`

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Join Implementation: Attempt #2

parent

```
void thread_join() {
      mutex_lock(&m);       // w
      if (!done)            // x
        cond_wait(&c, &m);// y
      mutex_unlock(&m);     // z
}
```

child

```
void thread_exit() {
      done = 1          // a
      cond_signal(&c);  // b
}
```

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Join Implementation: Attempt #2

parent

```
void thread_join() {
      mutex_lock(&m);        // w
      if (!done)             // x
        cond_wait(&c, &m);// y
      mutex_unlock(&m);     // z
}
```

child

```
void thread_exit() {
      done = 1              // a
      cond_signal(&c);  // b
}
```

fixed!

Example schedule:

parent			**w**	**x**	**y**	**z**
child	**a**	**b**				

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Join Implementation: Attempt #2

parent

```
void thread_join() {
      mutex_lock(&m);        // w
      if (!done)             // x
        cond_wait(&c, &m);// y
      mutex_unlock(&m);     // z
}
```

child

```
void thread_exit() {
      done = 1              // a
      cond_signal(&c);  // b
}
```

sleeps forever!

Example (bad) schedule:

Join Implementation: Attempt #3 (correct)

parent

```
void thread_join() {
      mutex_lock(&m);       // w
      if (!done)            // x
        cond_wait(&c, &m);// y
      mutex_unlock(&m);     // z
}
```

child

```
void thread_exit() {
      mutex_lock(&m);  // a
      done = 1          // b
      cond_signal(&c); // c
      mutex_unlock(&m);// d
}
```

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Join Implementation: Attempt #3 (correct)

parent

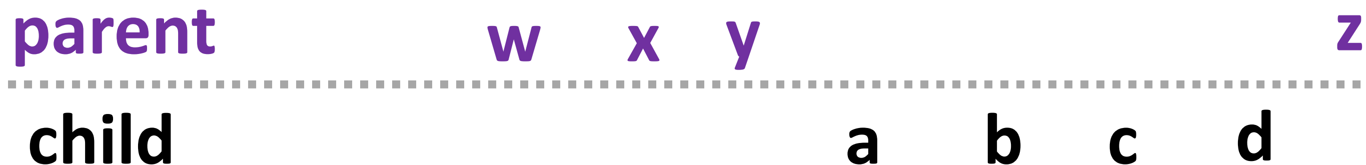
```
void thread_join() {
      mutex_lock(&m);     // w
      if (!done)          // x
        cond_wait(&c, &m);// y
      mutex_unlock(&m);   // z
}
```

child

```
void thread_exit() {
      mutex_lock(&m);  // a
      done = 1         // b
      cond_signal(&c); // c
      mutex_unlock(&m);// d
}
```

fixed!

Example chedule:



Signaling between threads

Bounded Buffer (producer-consumer queue)

Signaling between threads

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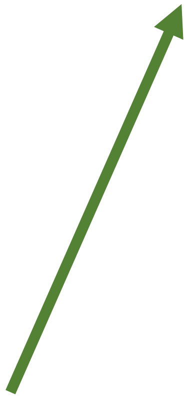
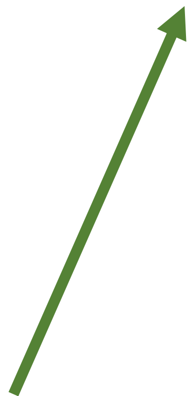


t1: put()

Signaling between threads

Bounded Buffer (producer-consumer queue)



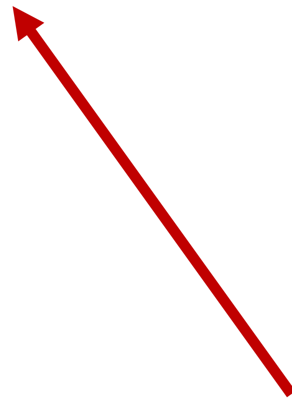
`t1: put()`

Signaling between threads

t2: `take()`

Signaling between threads

Bounded Buffer (producer-consumer queue)

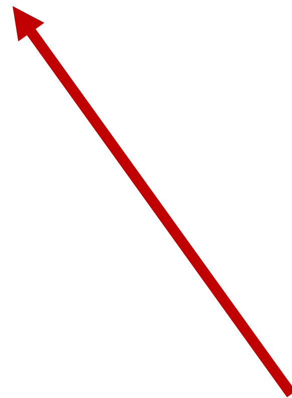


t2: `take()`

Signaling between threads

Signaling between threads

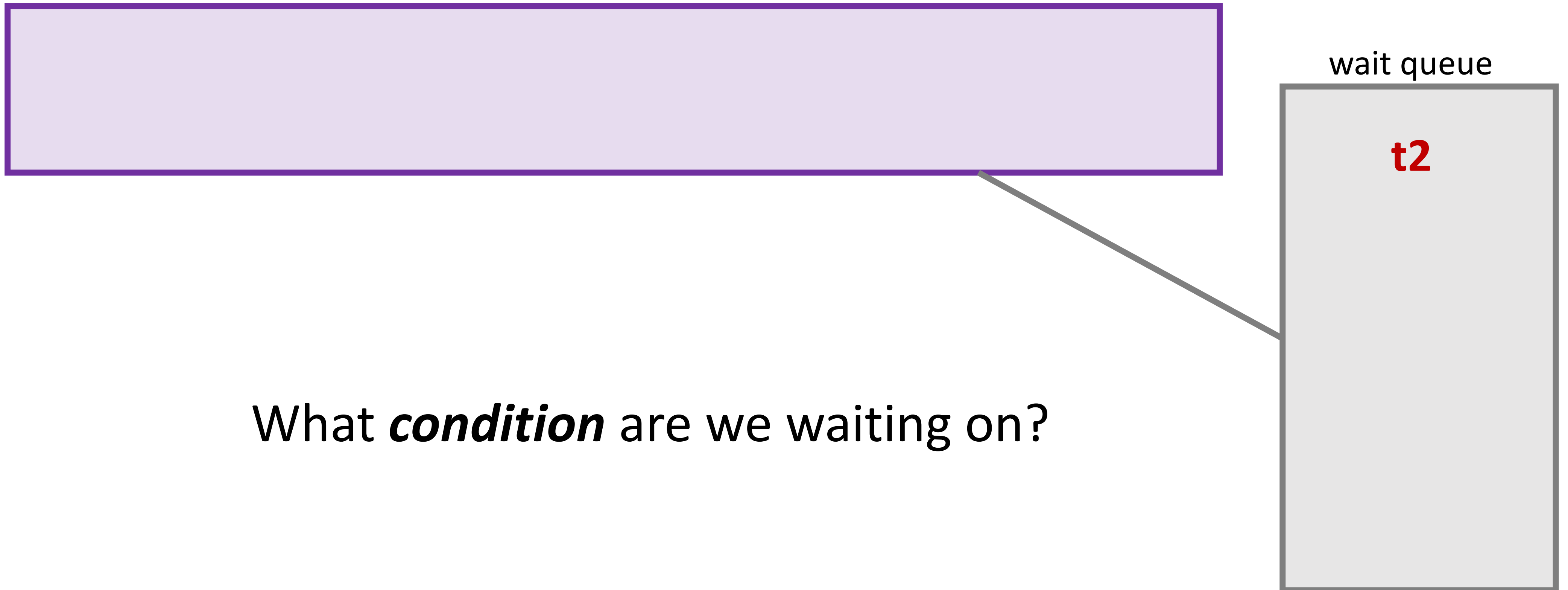
Bounded Buffer (producer-consumer queue)



???

`t2: take()`

Signaling between threads



Signaling between threads

Signaling between threads

Bounded Buffer (producer-consumer queue)

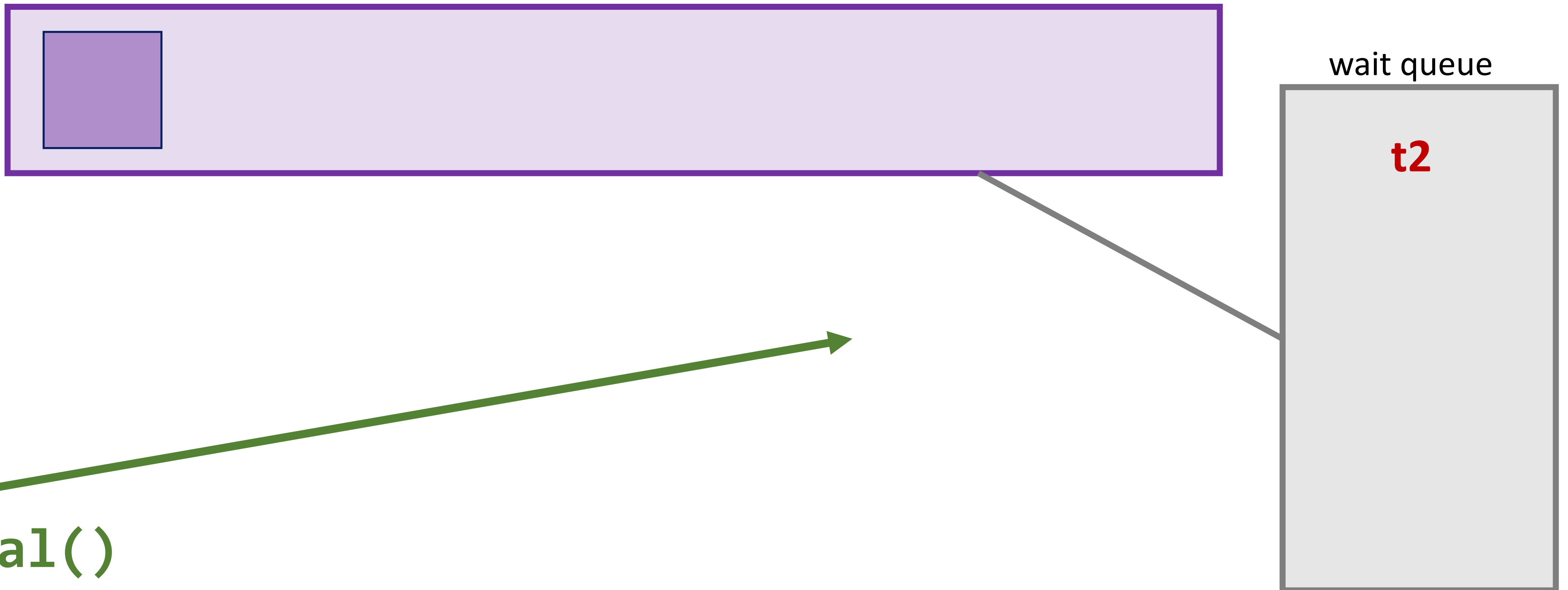
wait queue

t2

t1: put()

What should happen?

Signaling between threads



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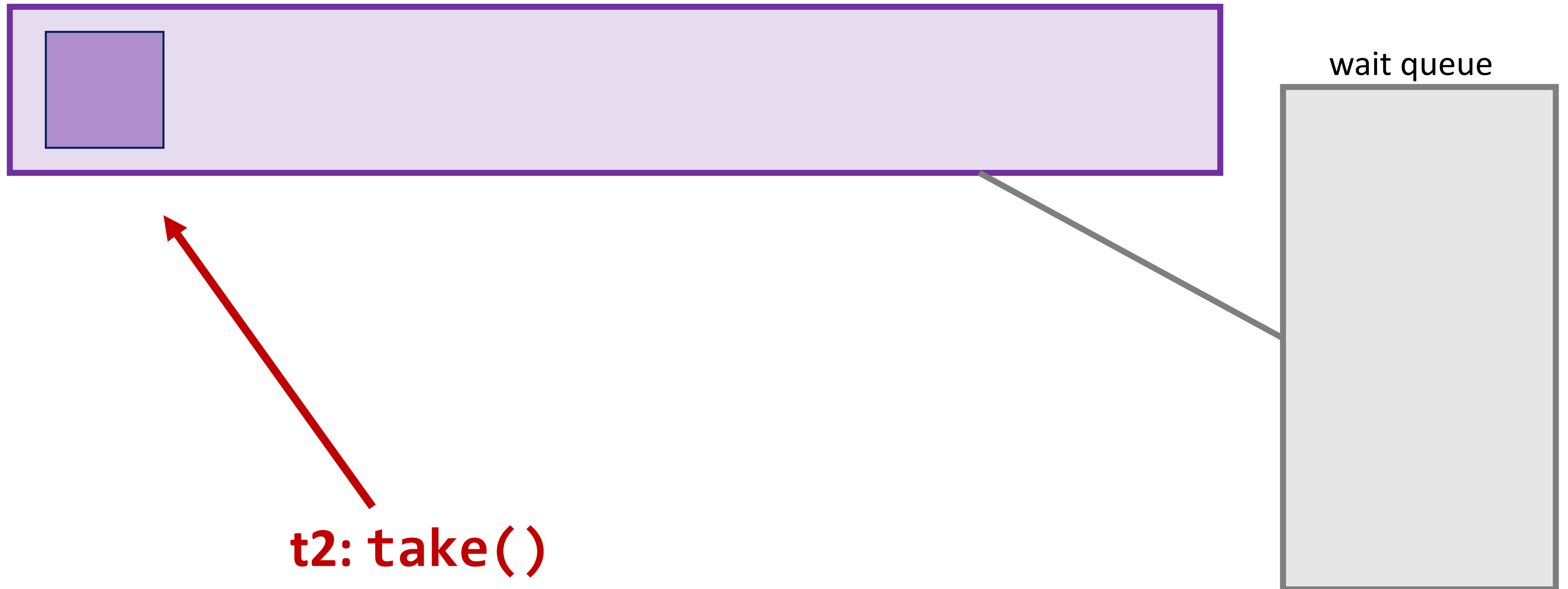
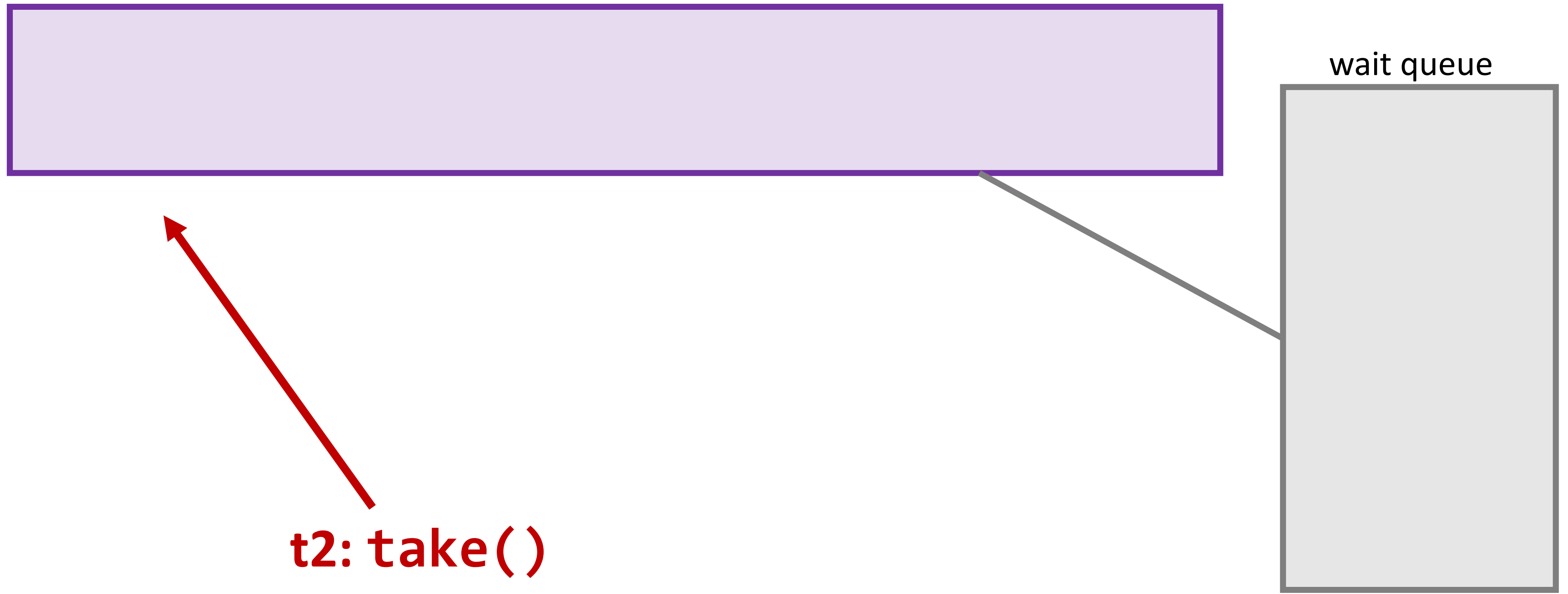


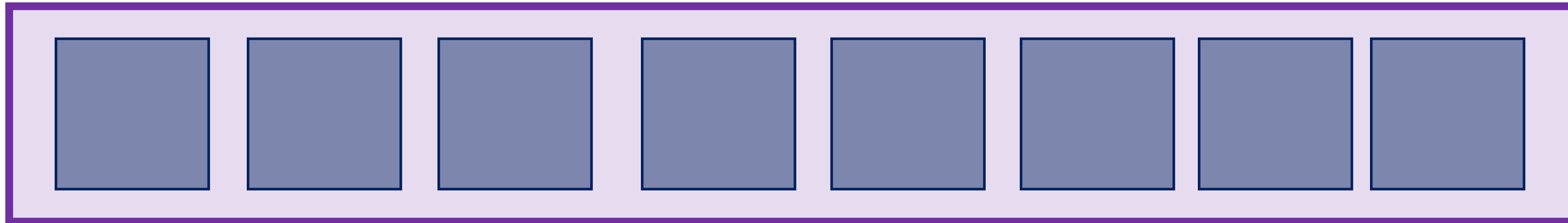
Signaling between threads



The queue is a *circular queue*

- Also sometimes called a *ring buffer*

Bounded Buffer (producer-consumer queue)



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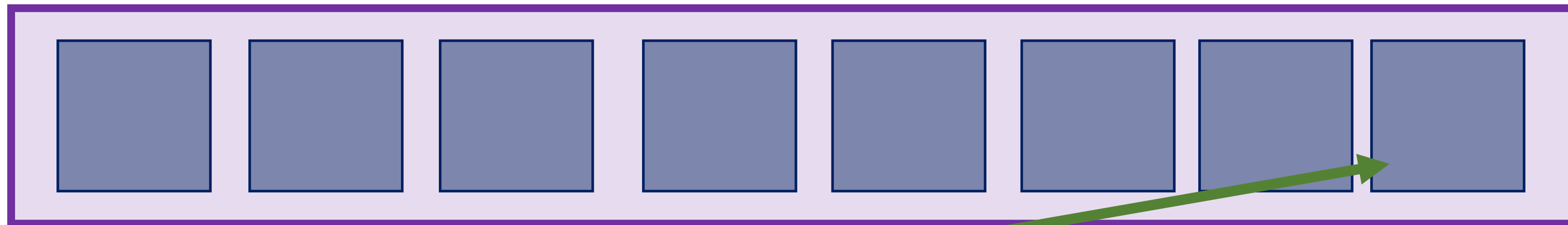

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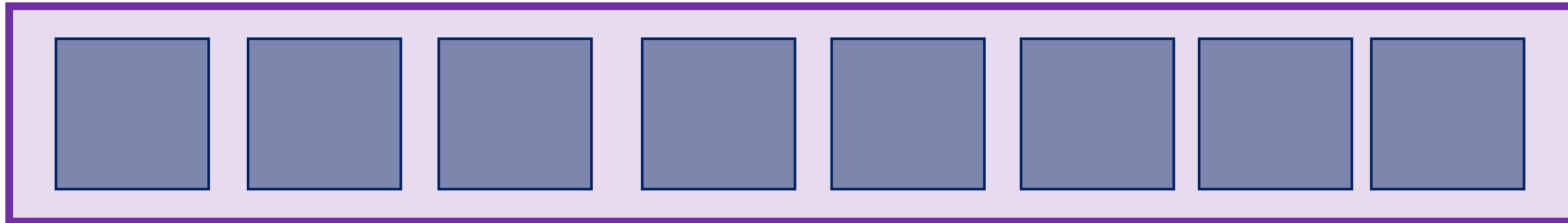

We’re full

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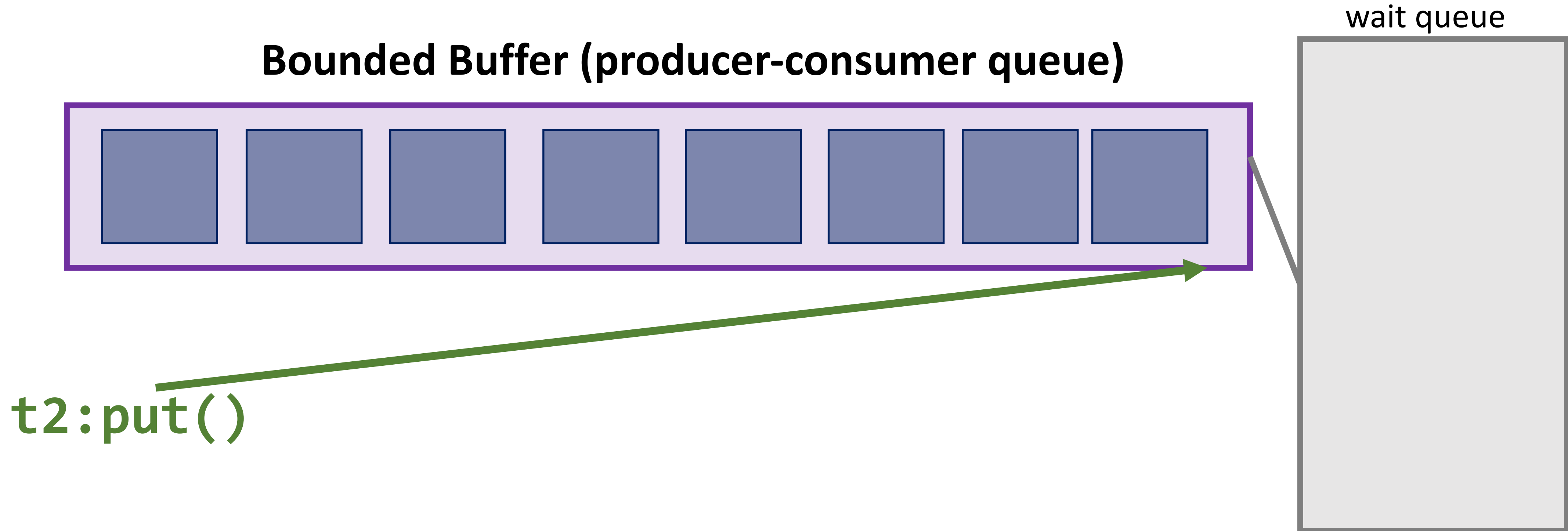

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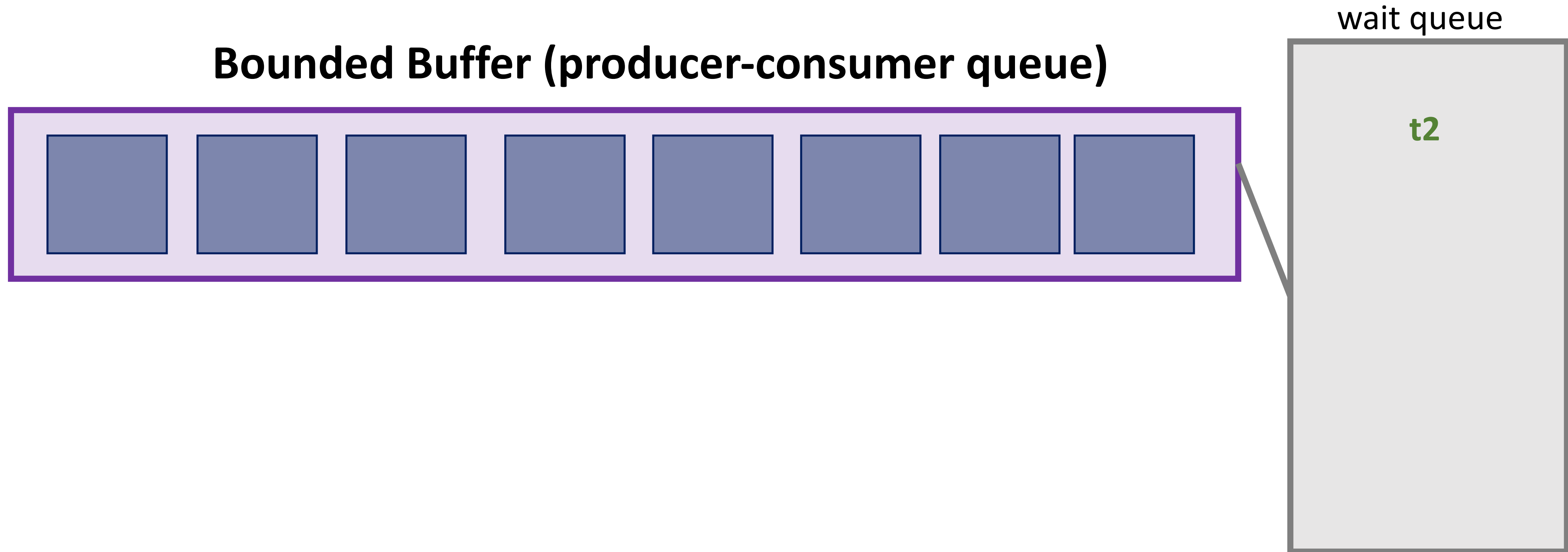

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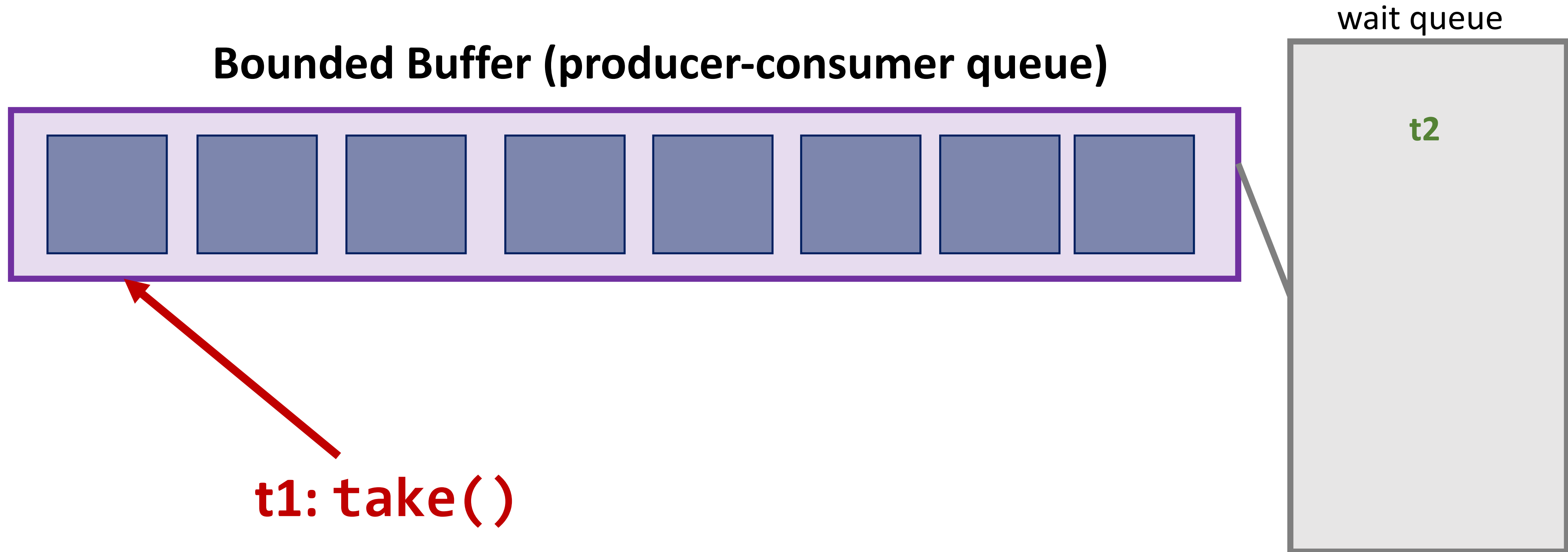

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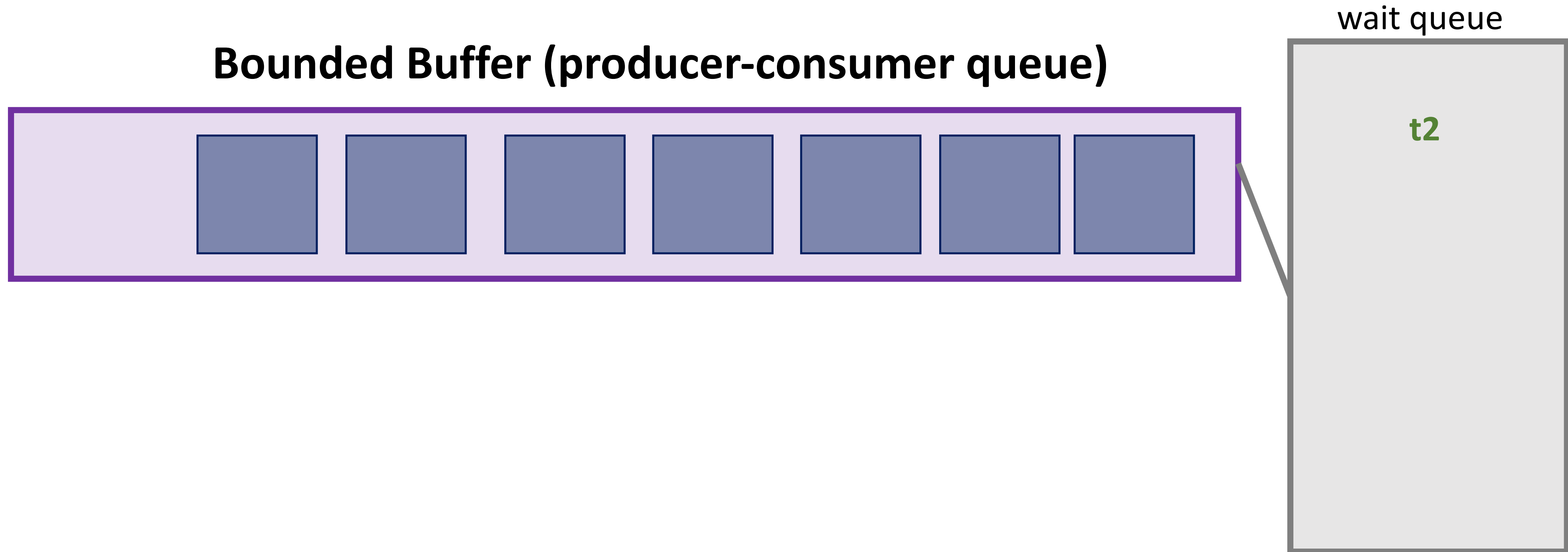

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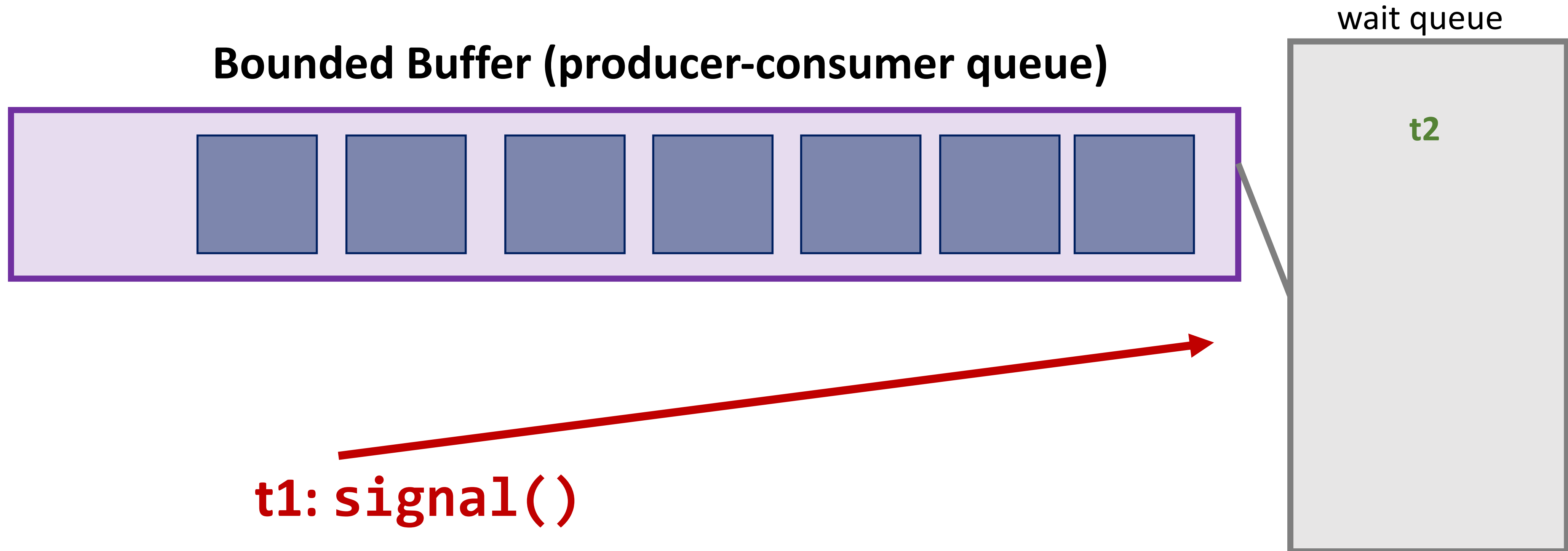

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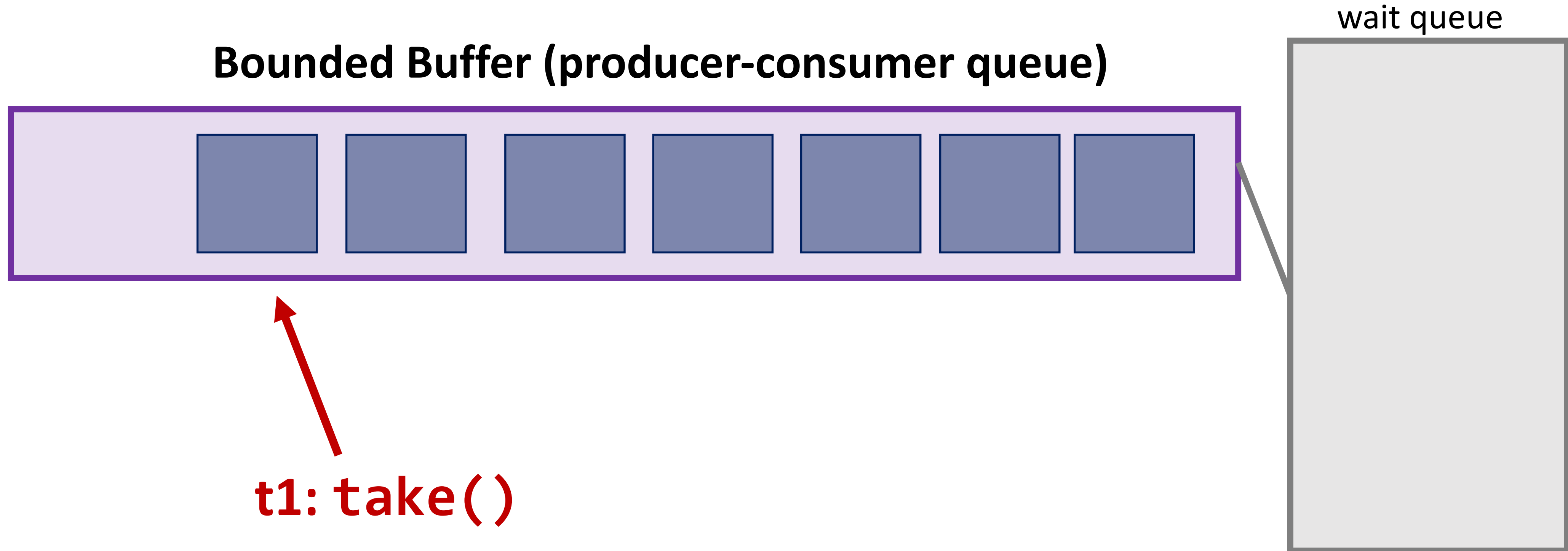
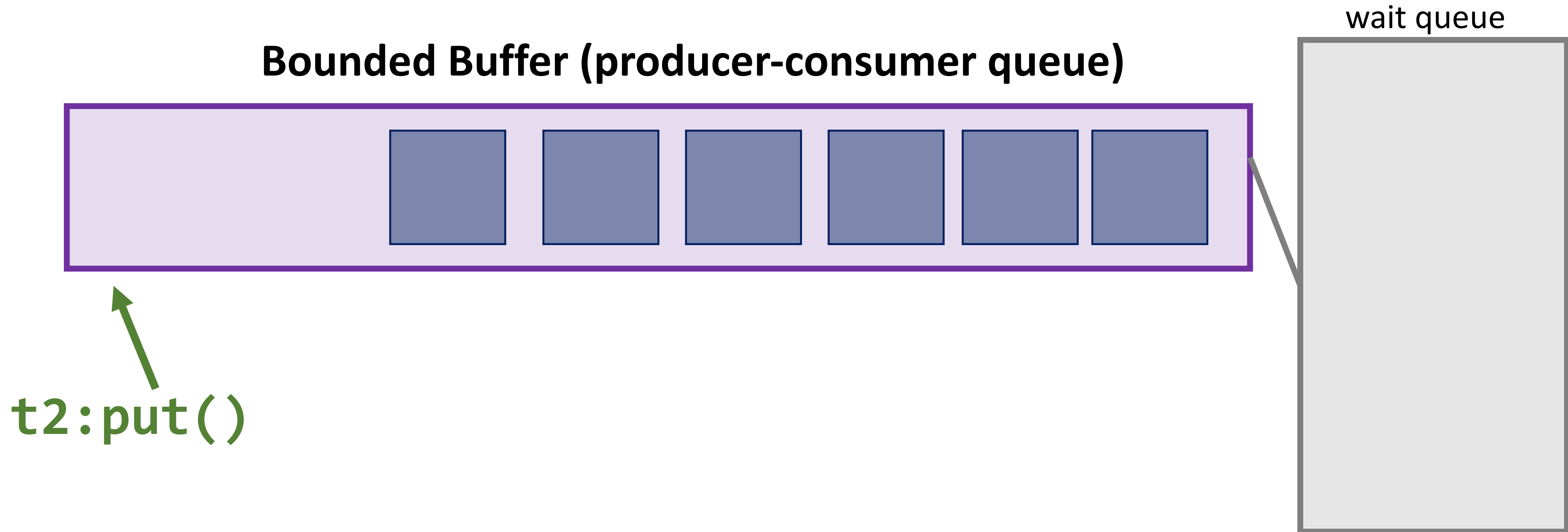


The queue is a *circular queue*

- Also sometimes called a *ring buffer*



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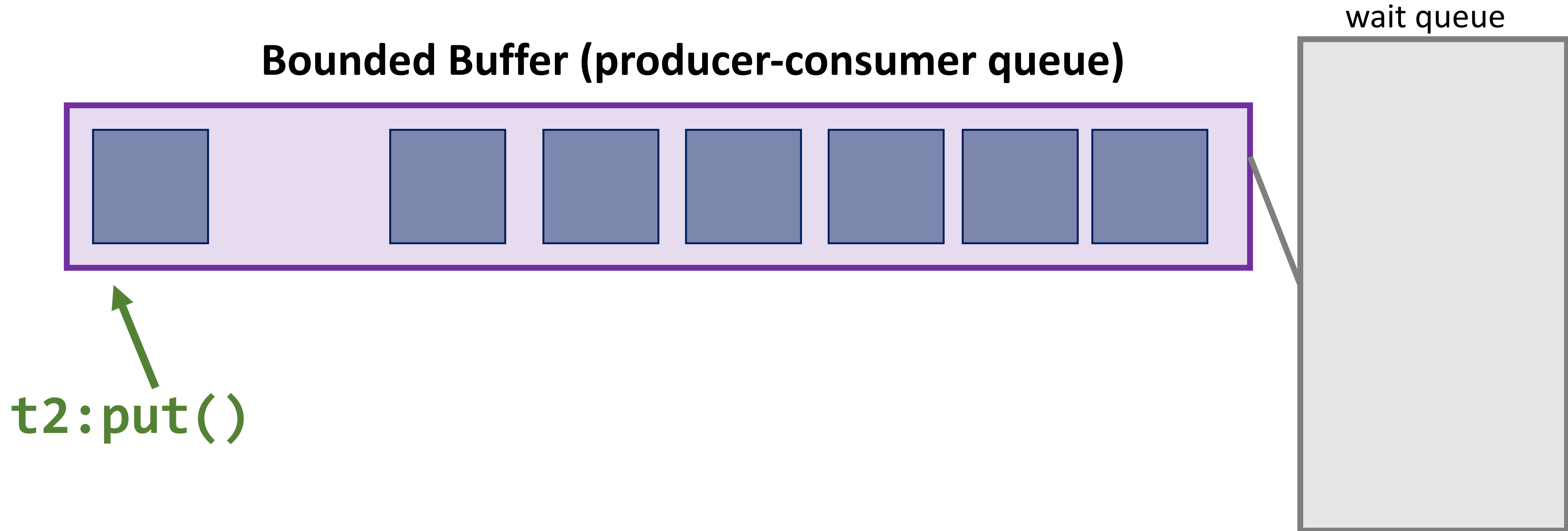
- Also sometimes called a *ring buffer*



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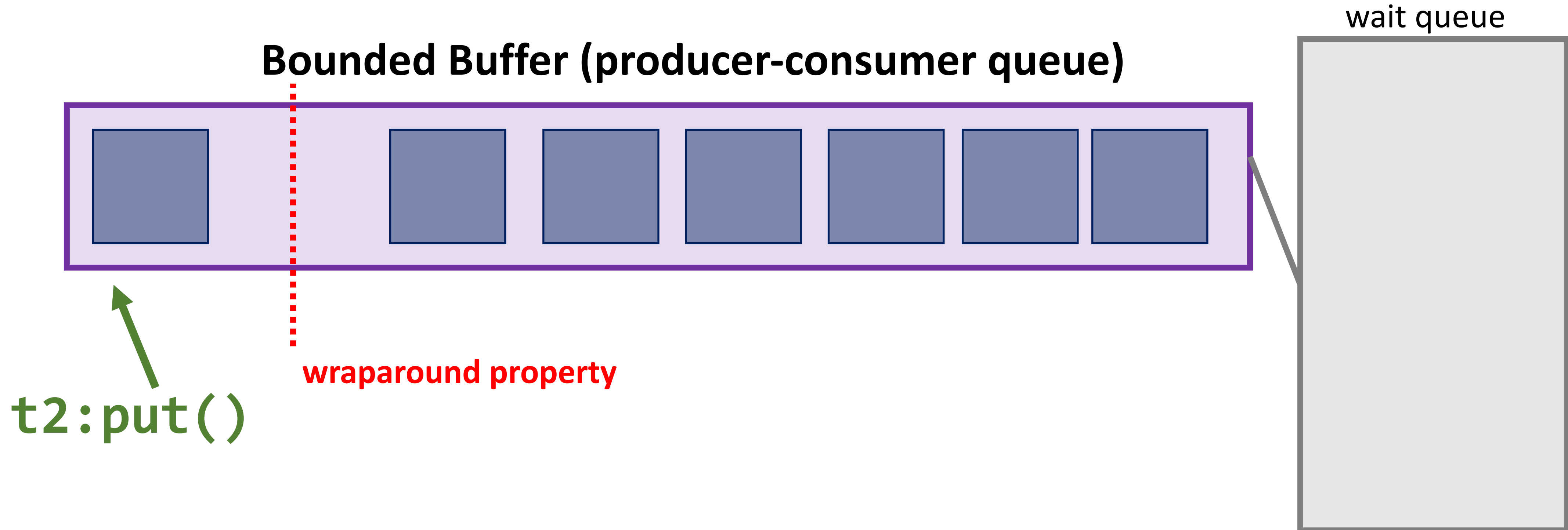

Bounded Buffer

- **Reads and writes** to buffer **require locking**
- when buffers are ***full***, writers wait()
- when buffers are ***empty***, readers wait()
- Many programming languages expose this abstraction directly
  - **`chan`** in Go
  - **`channel`** in Julia
  - Python requires a **`queue()`** with a **`lock()`**
  - Rust might use **`CircularBuffer()`** and **`CondVar()`** maybe `crossbeam_channel()`

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Bounded Buffer

- **Producers** generate data
- **Consumers** take data and process it
- ***Very frequent*** situation encountered in systems programming
- General strategy: use CVs to notify:
  - waiting readers when data is available
  - waiting writers when slots are free

Example

- Easy case:
  - 1 consumer thread
  - 1 producer thread
  - 1 shared buffer (max slots=1)

  - `numfill` is buffer slots currently filled
  - let's start with some code that doesn't *quite* work

numfull = 0

[RUNNABLE]

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

[RUNNING]

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

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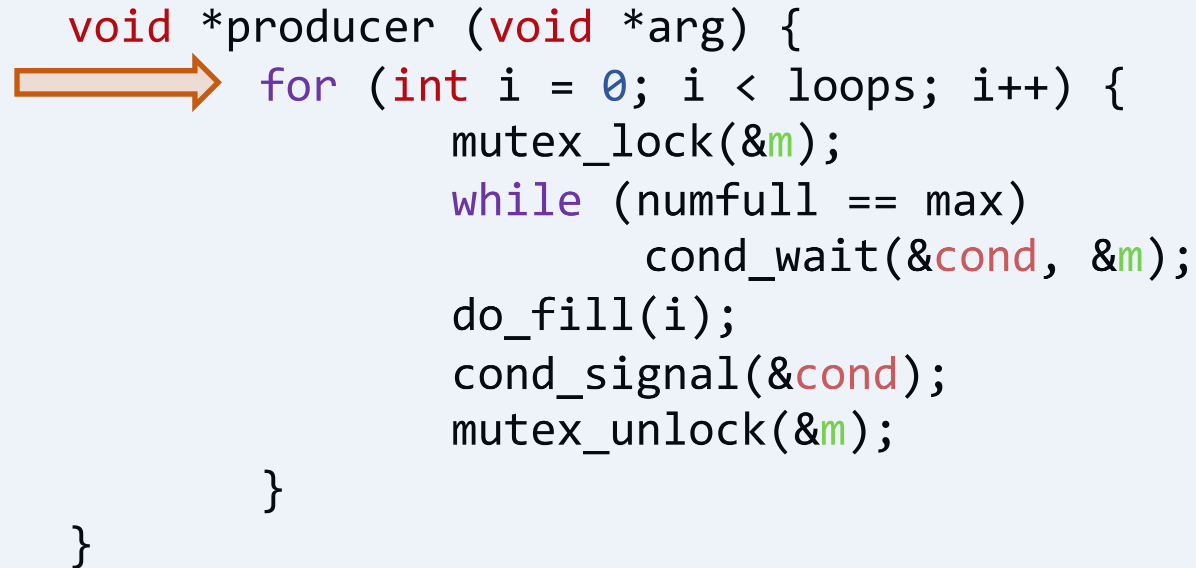

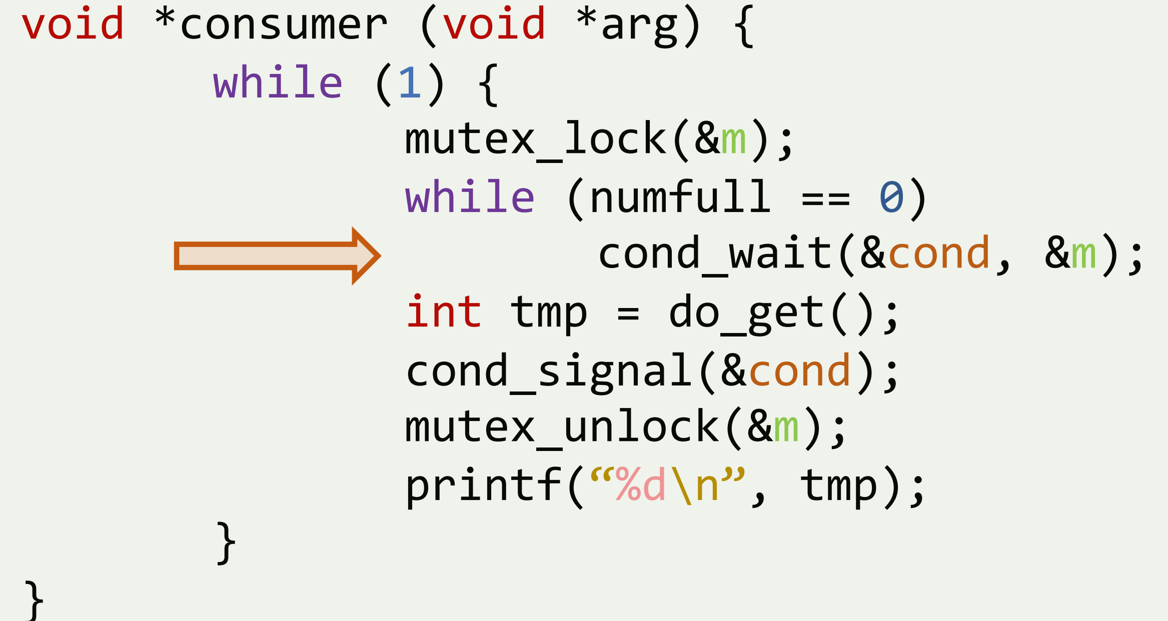

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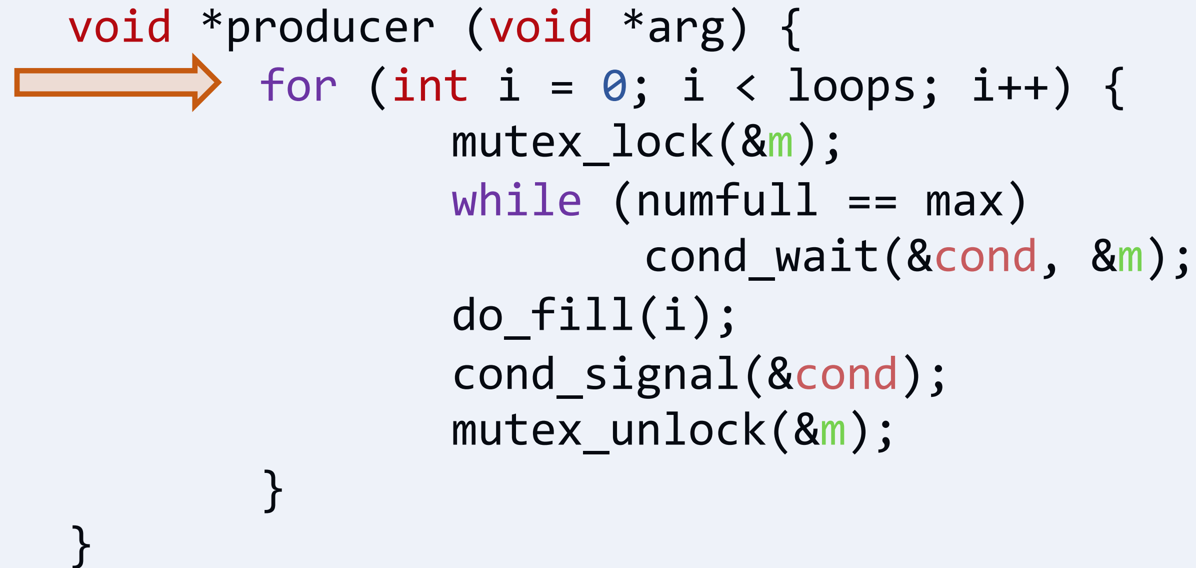

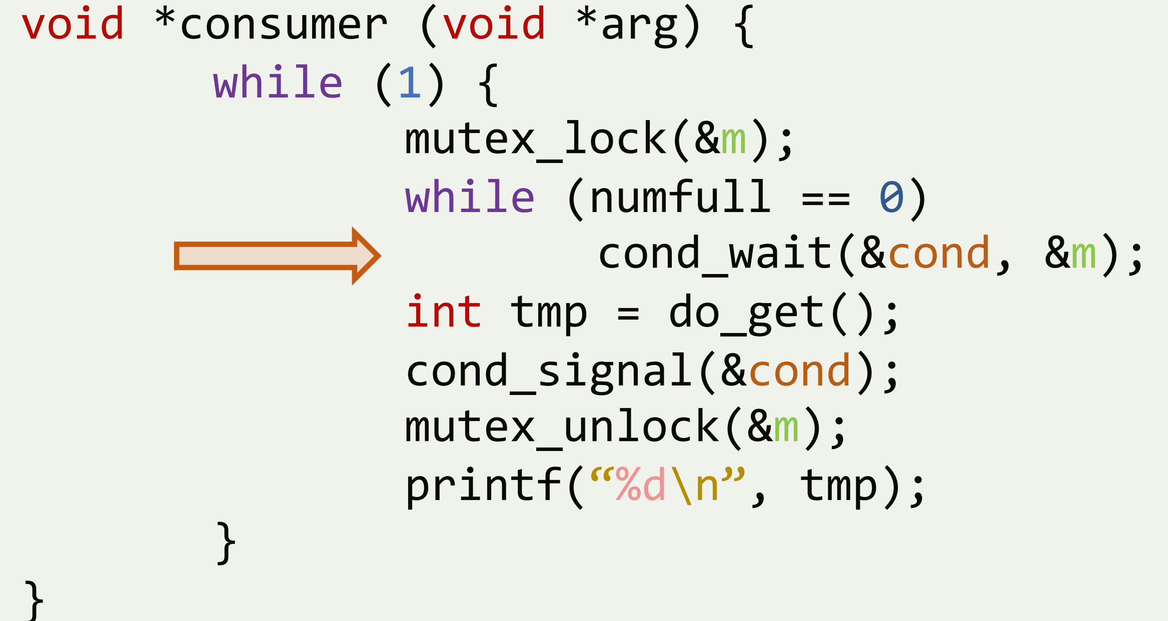

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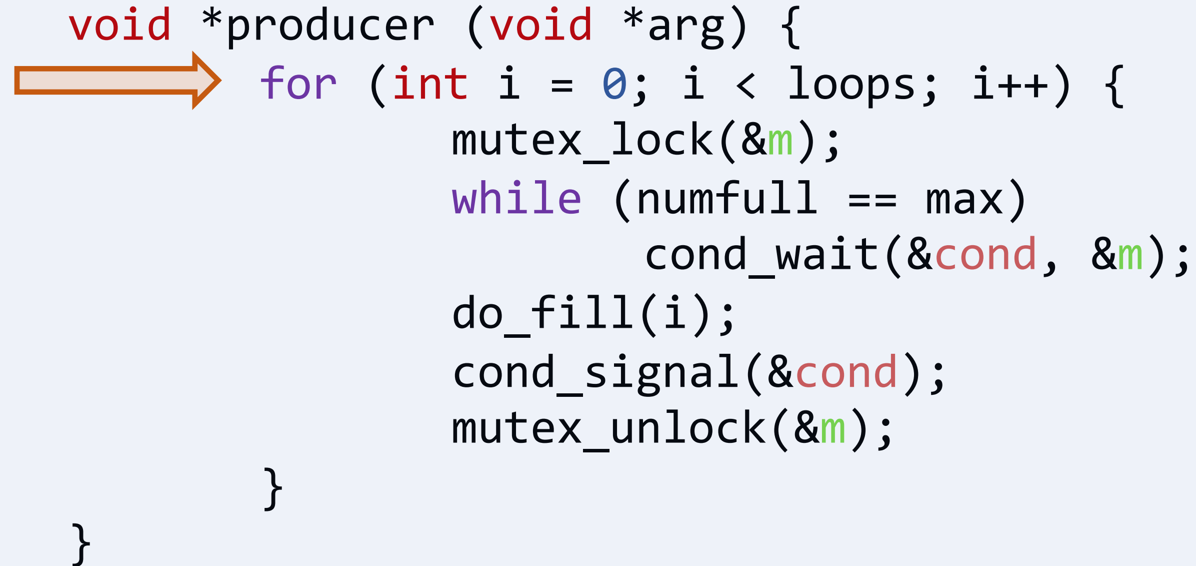

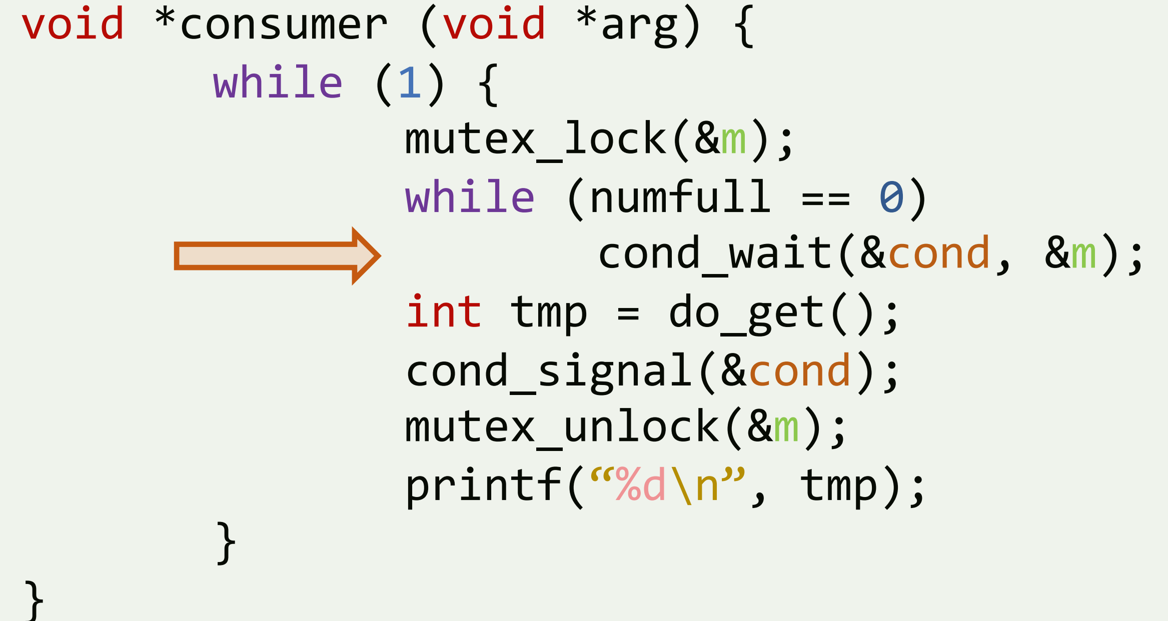

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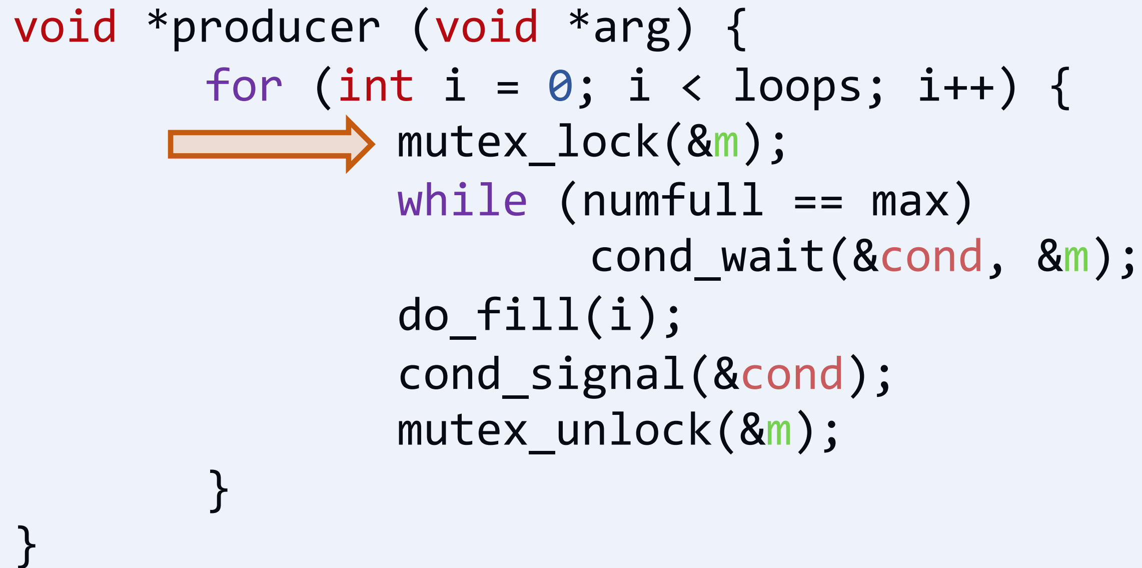

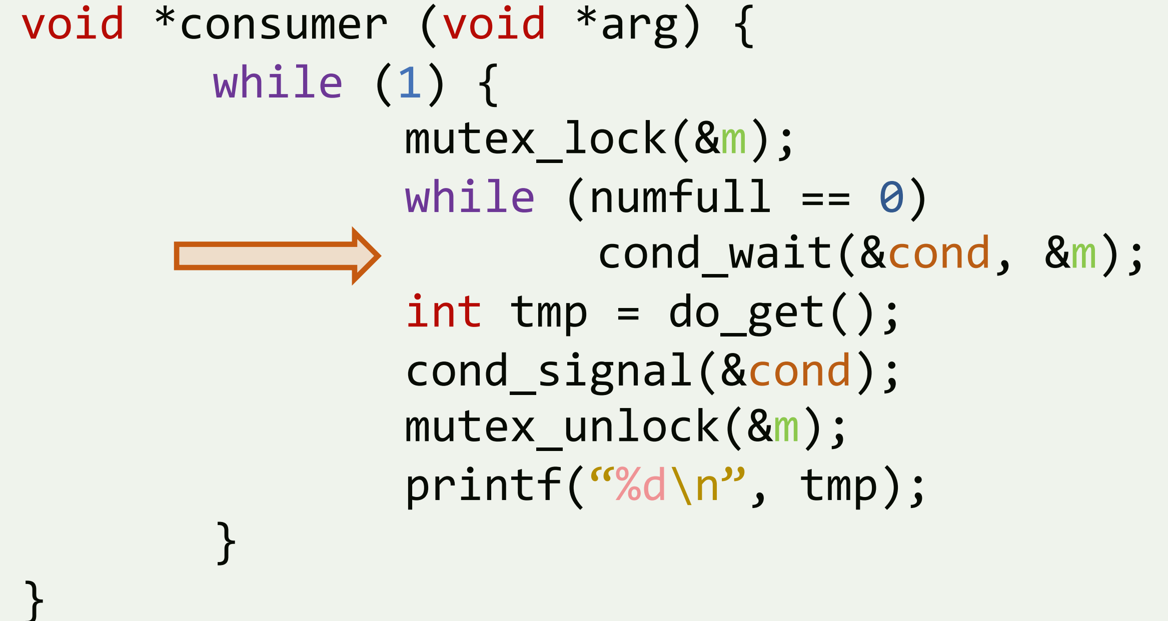

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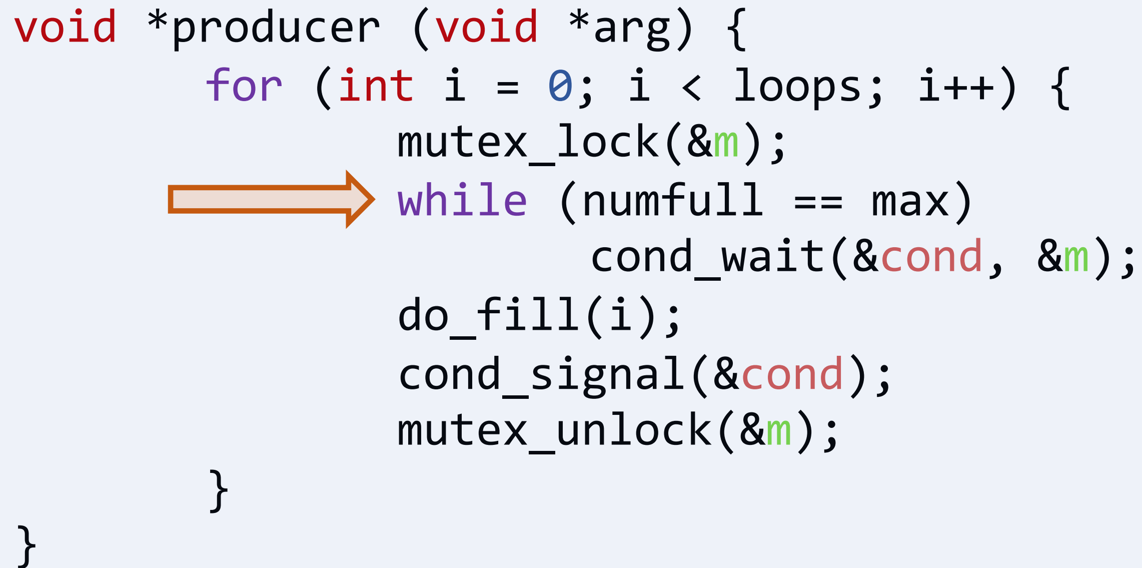
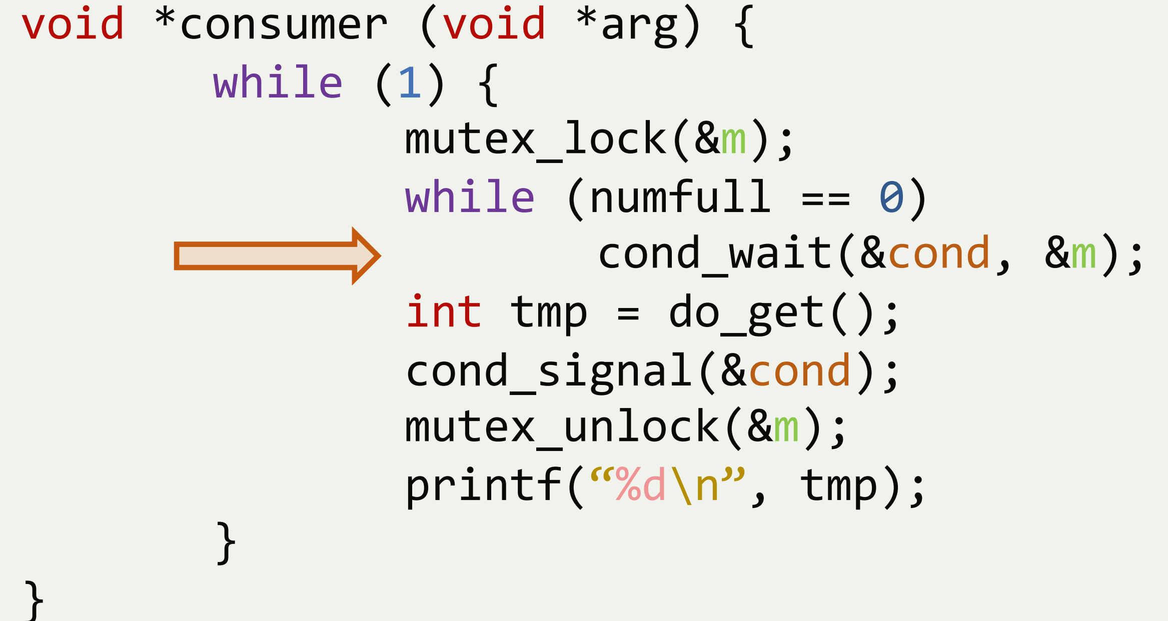


[SLEEPING]



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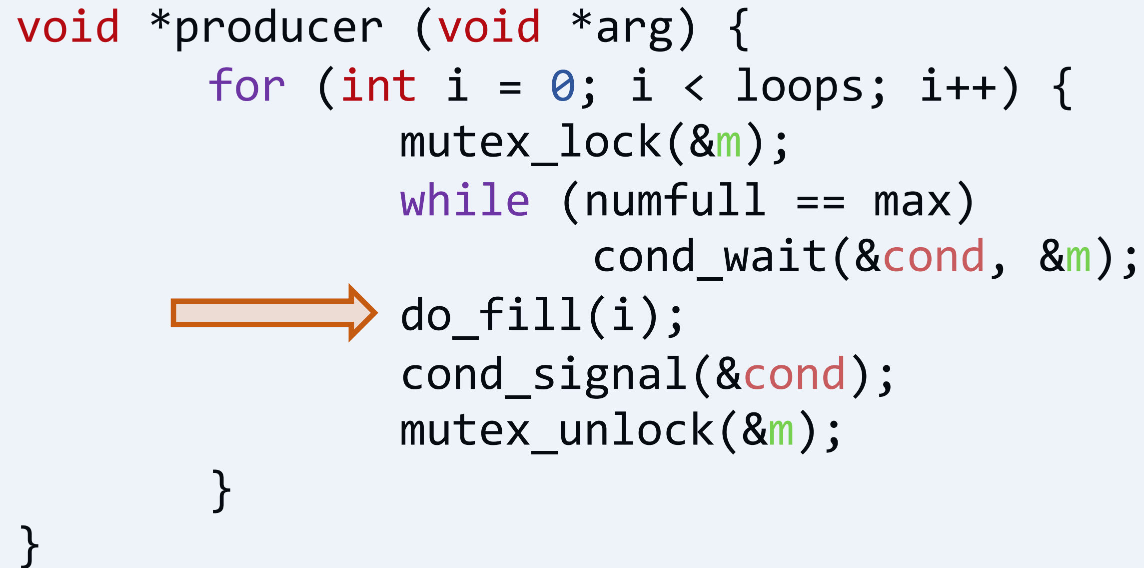

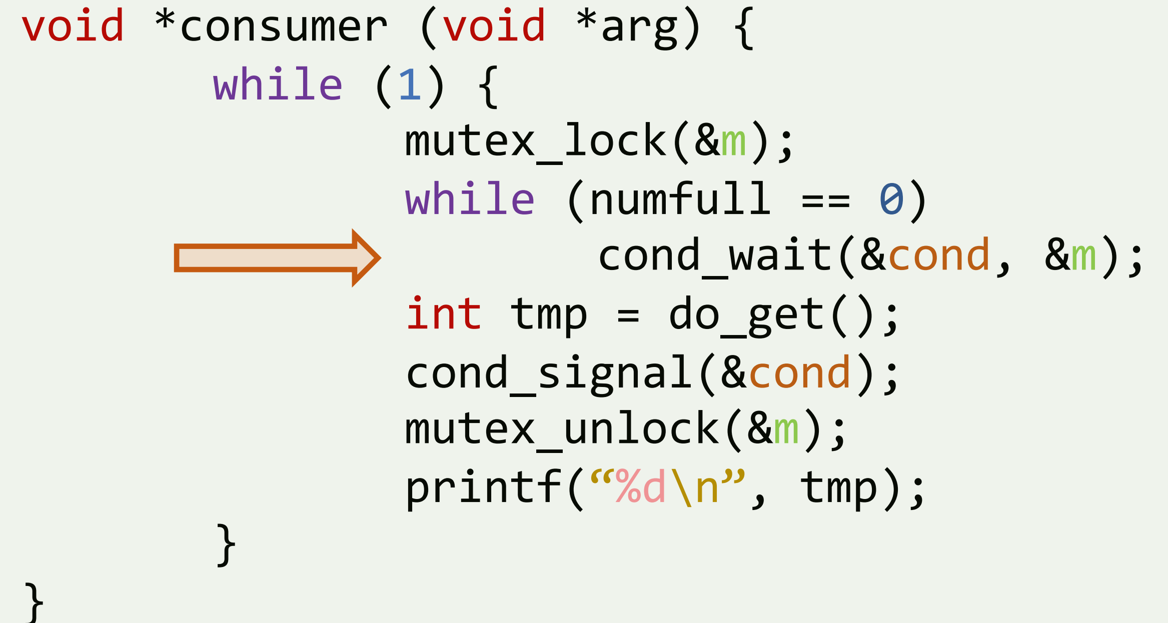

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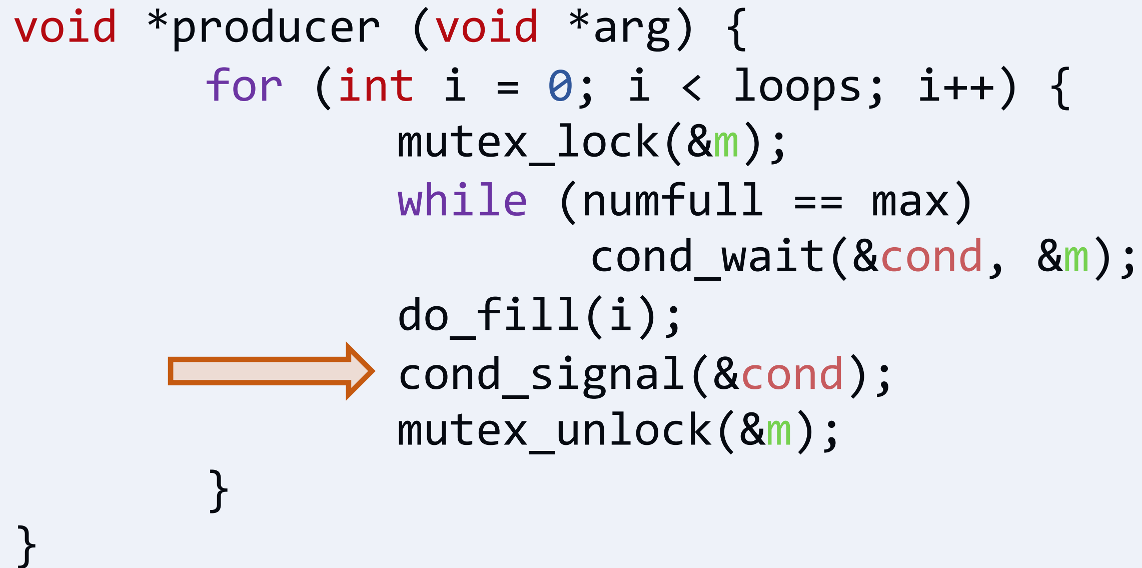


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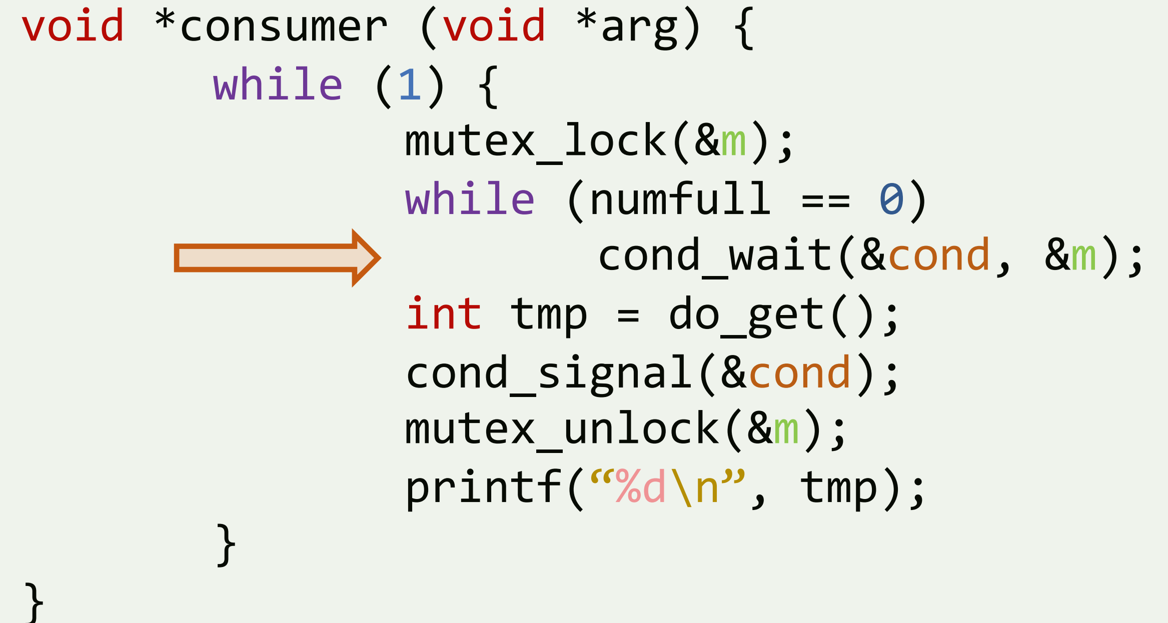


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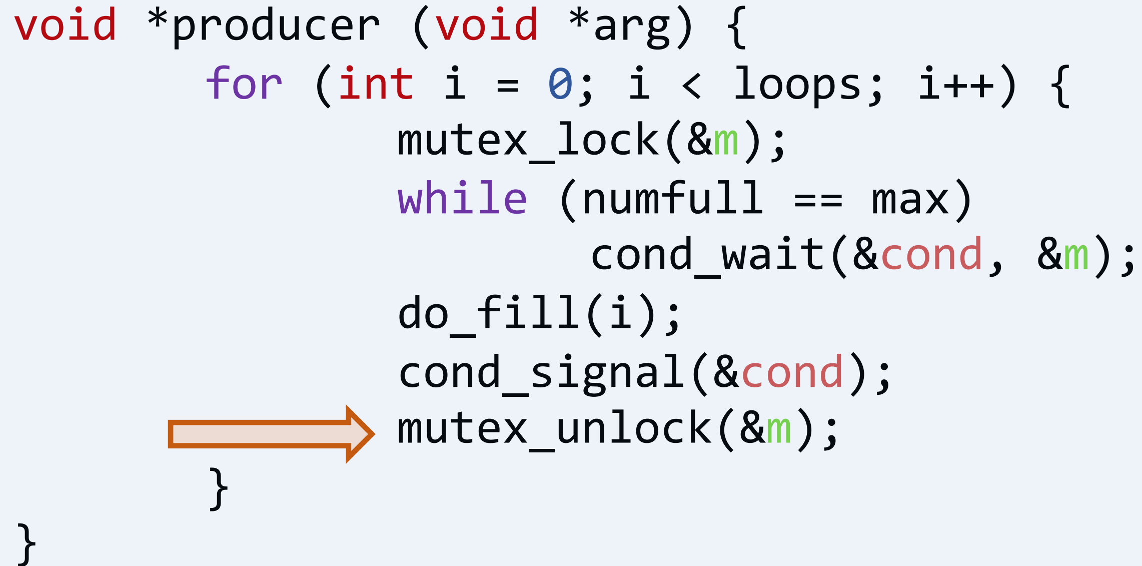

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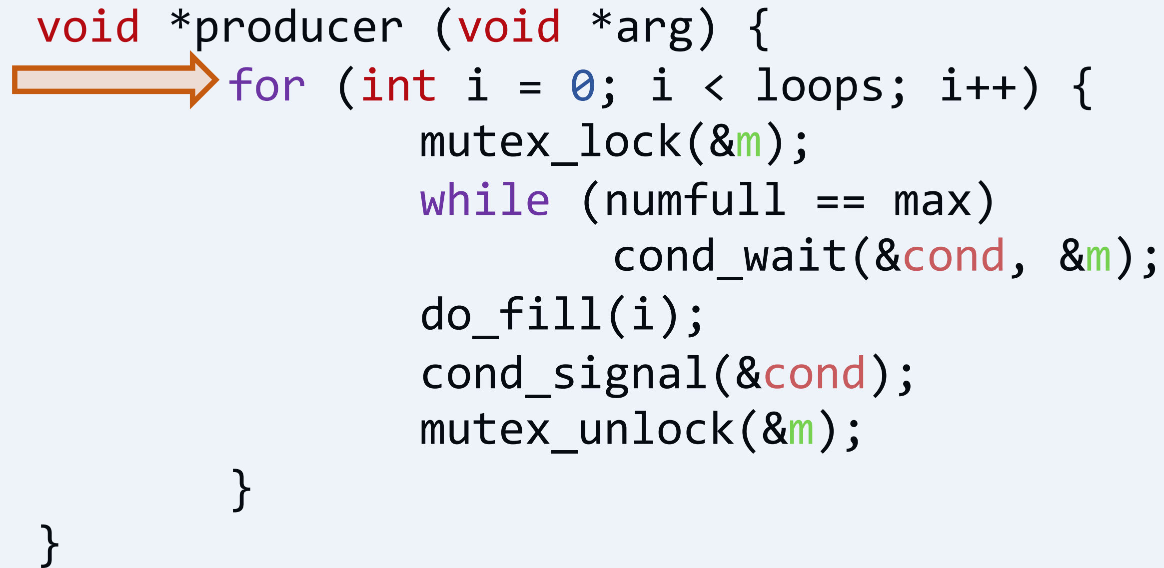

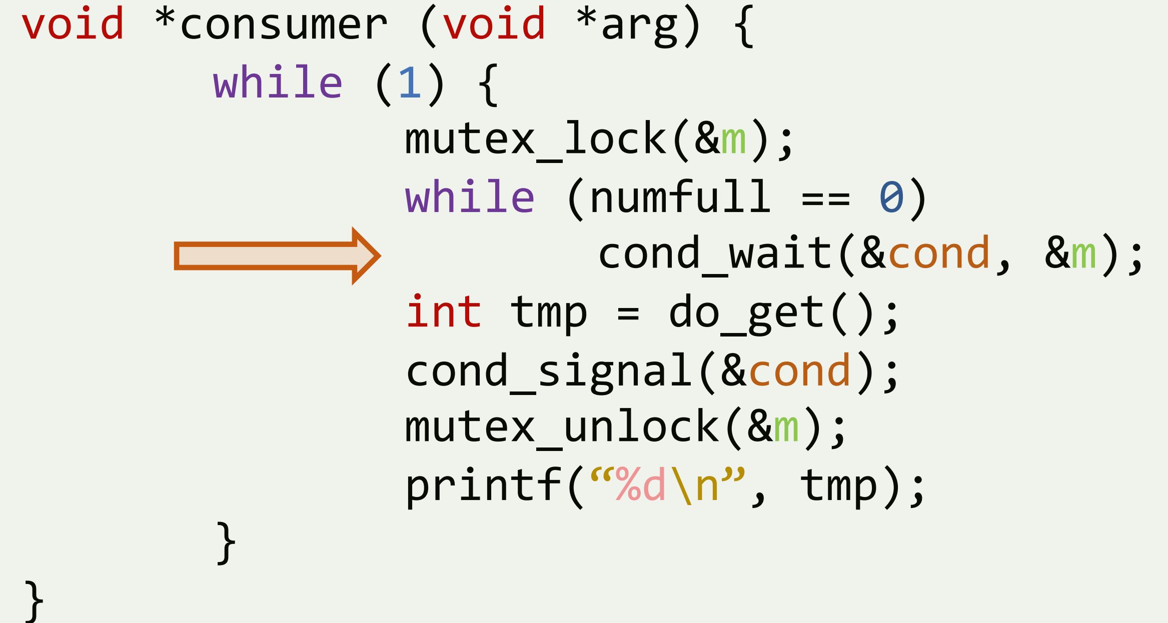

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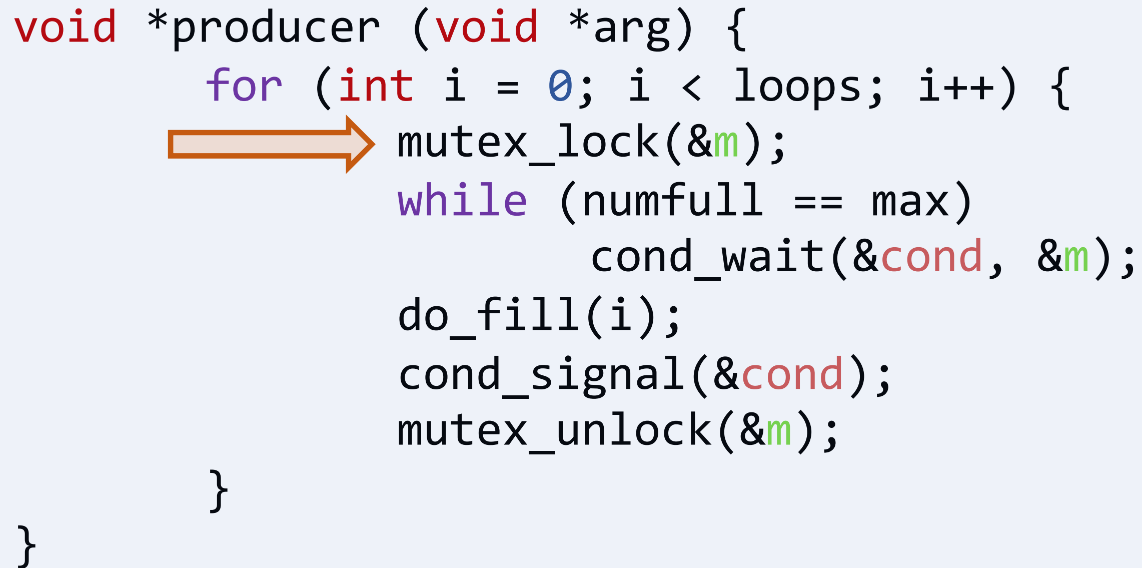

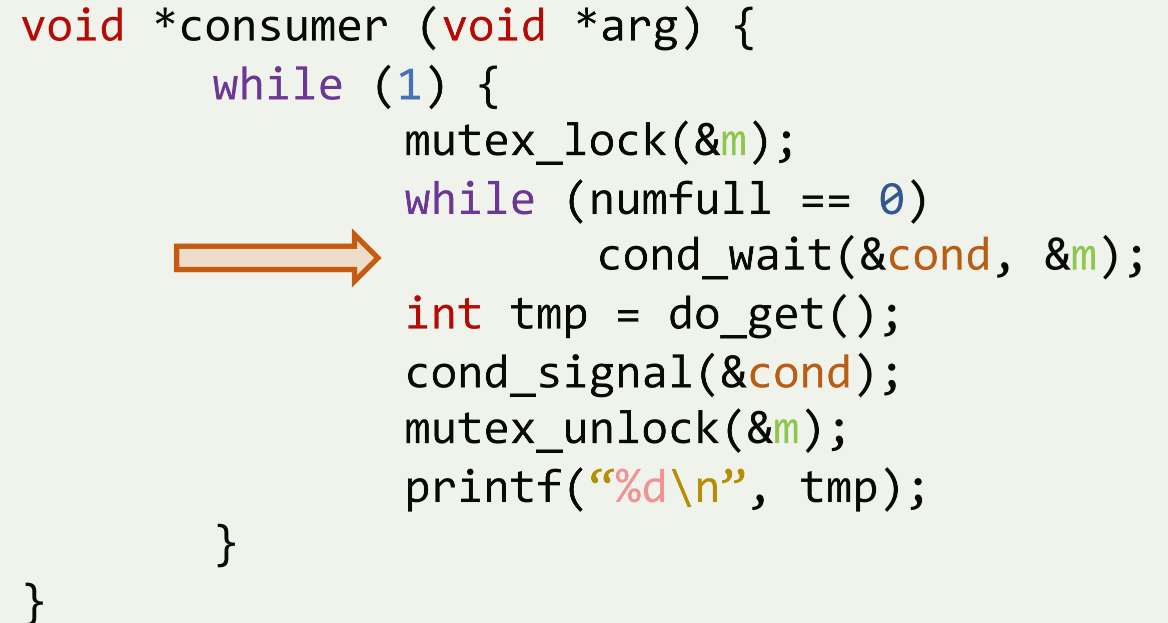

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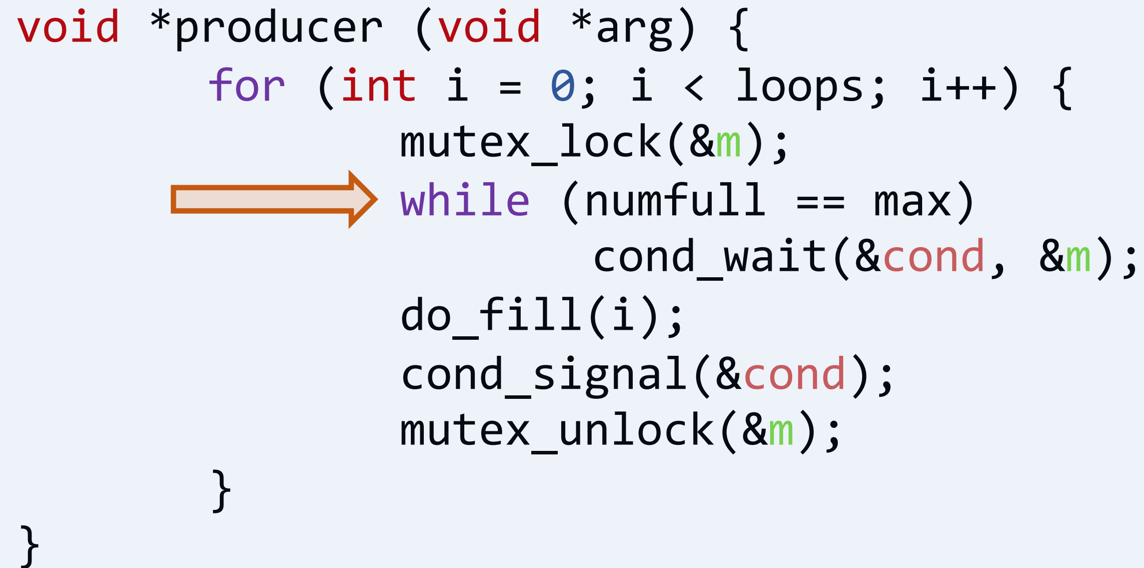


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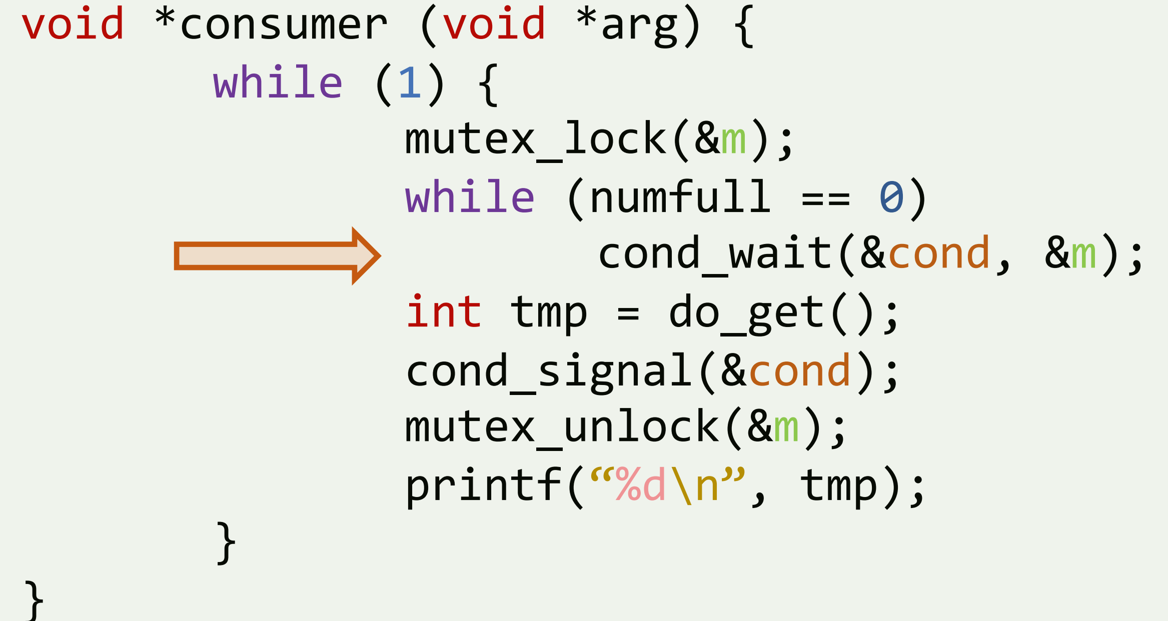


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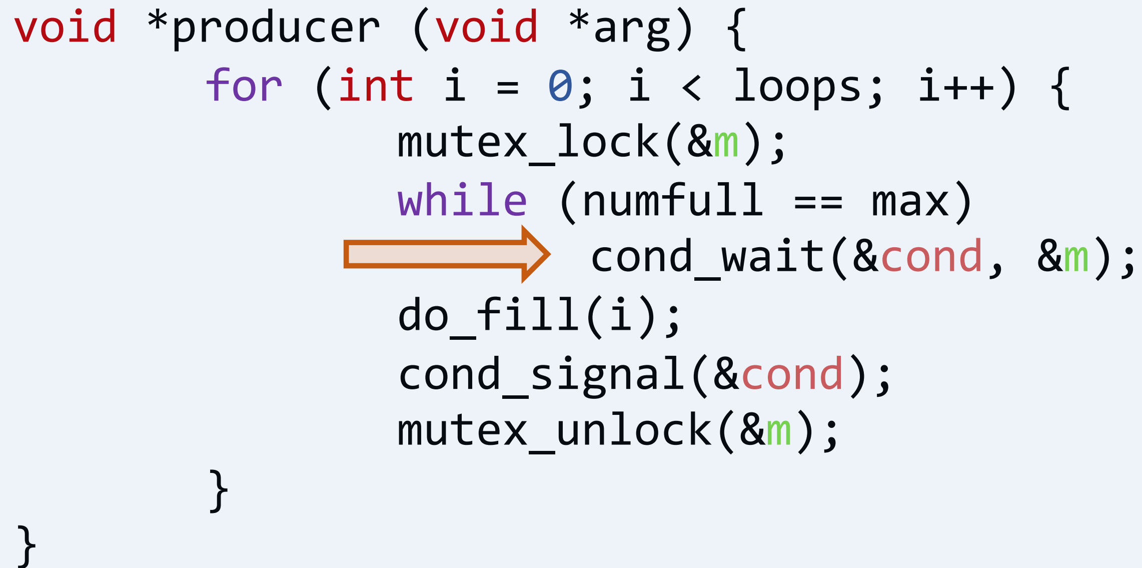

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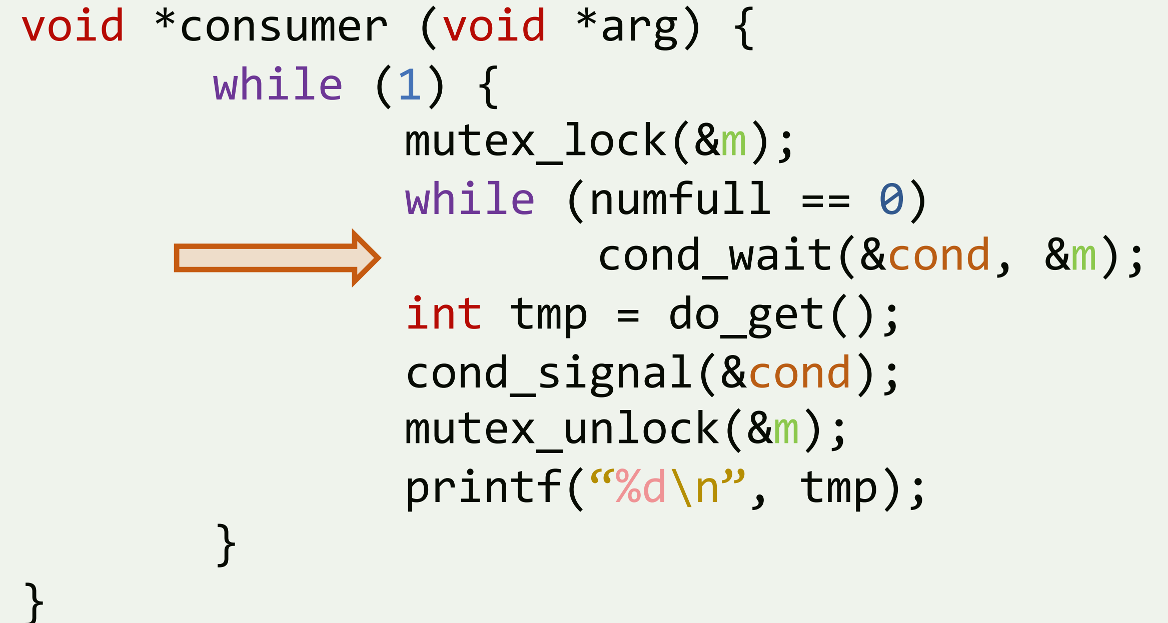

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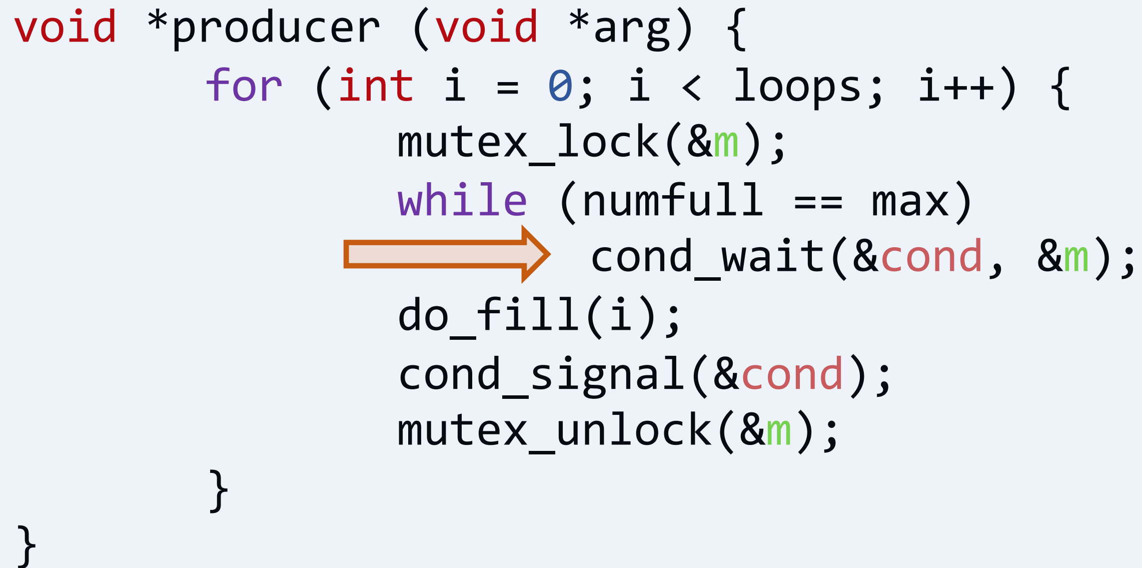

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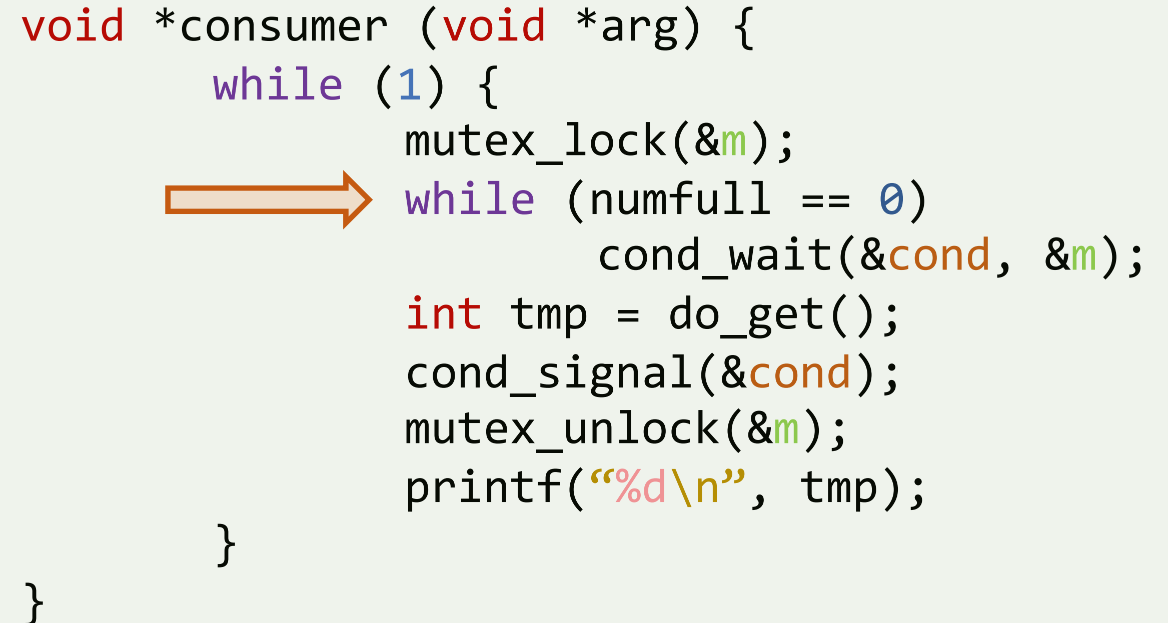

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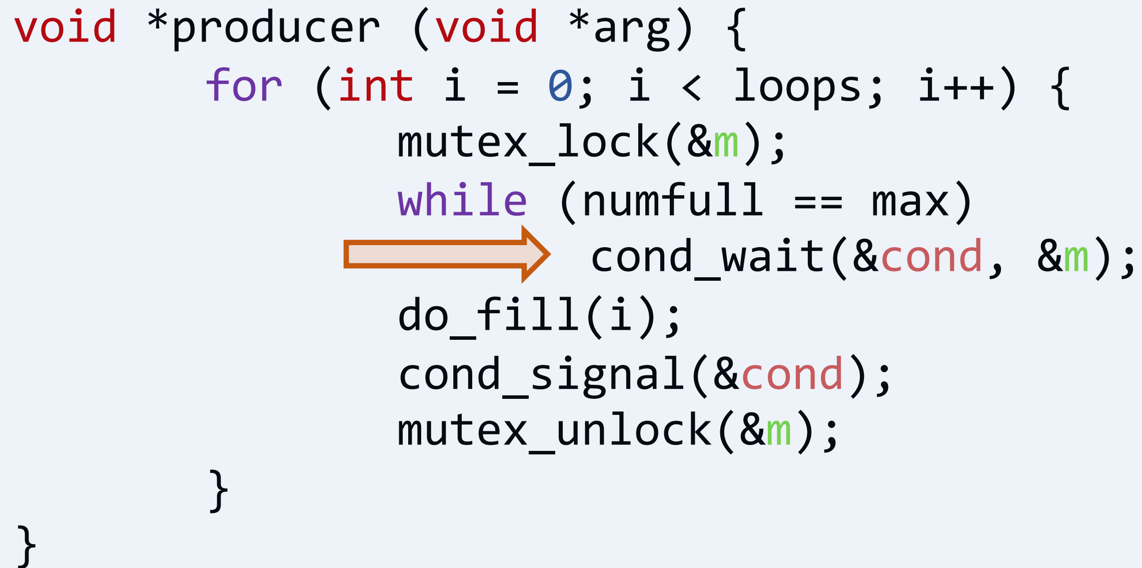

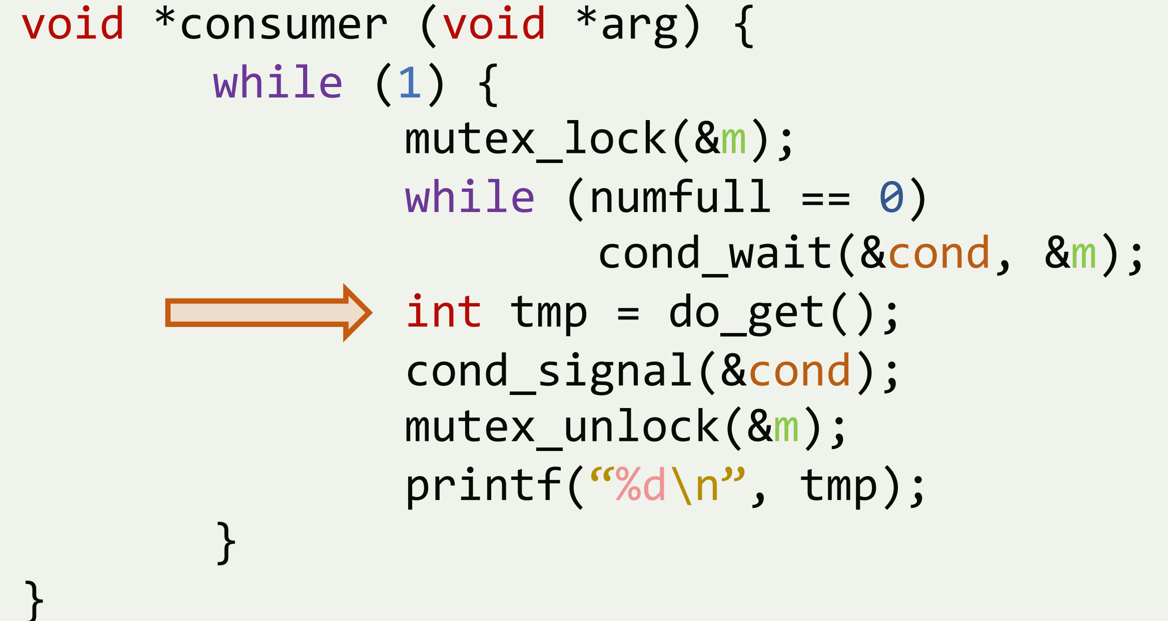

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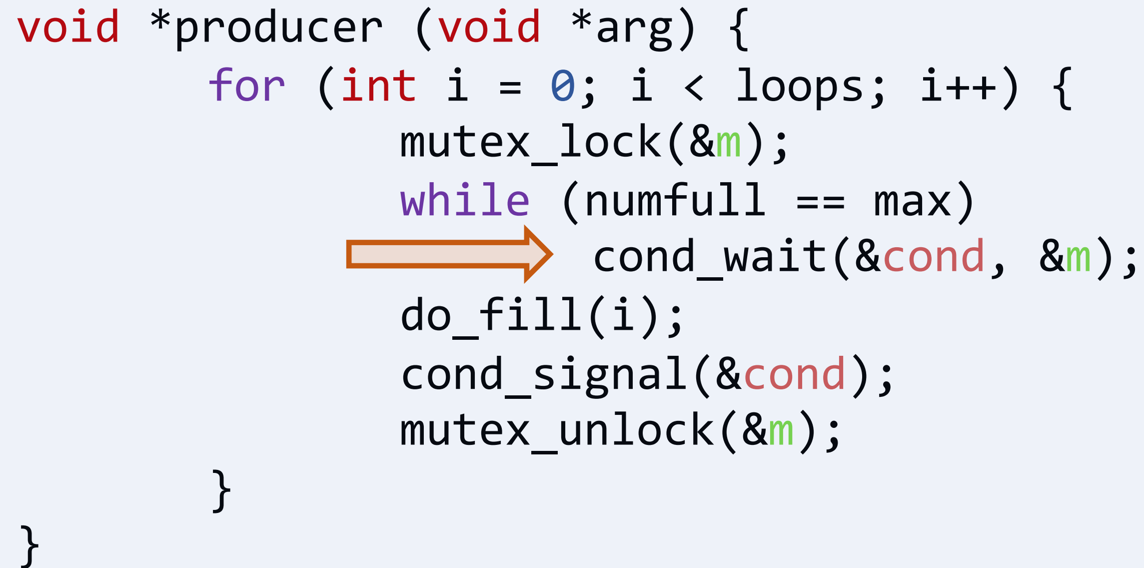

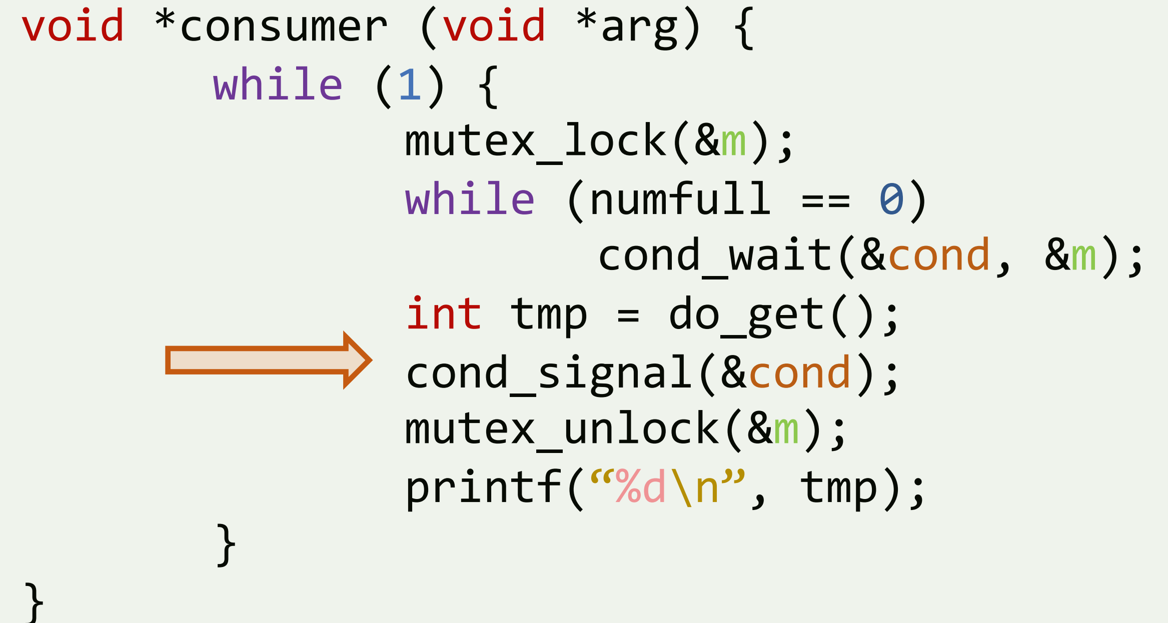

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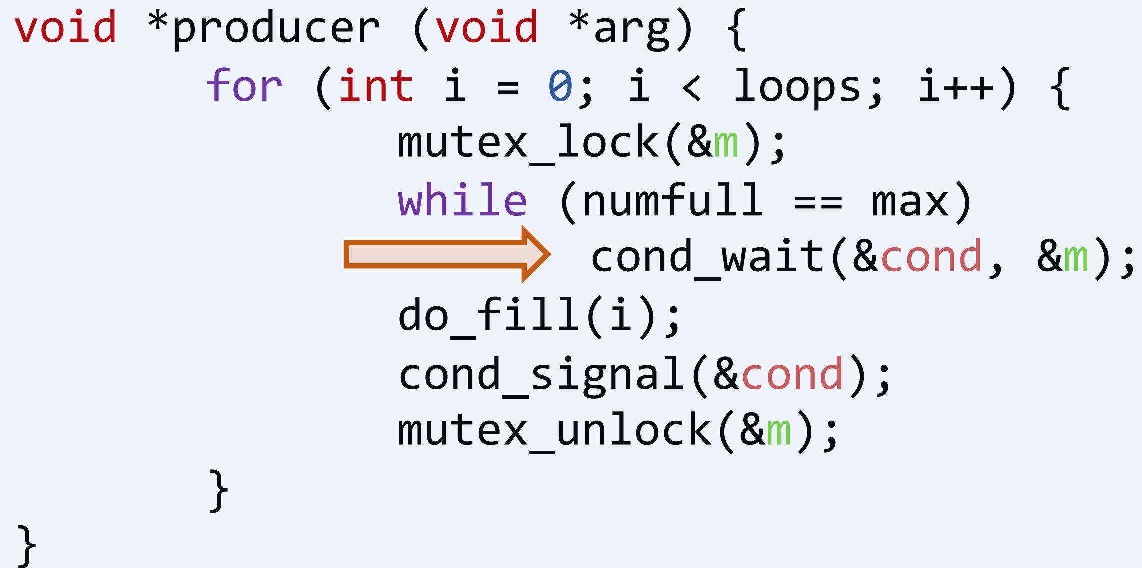

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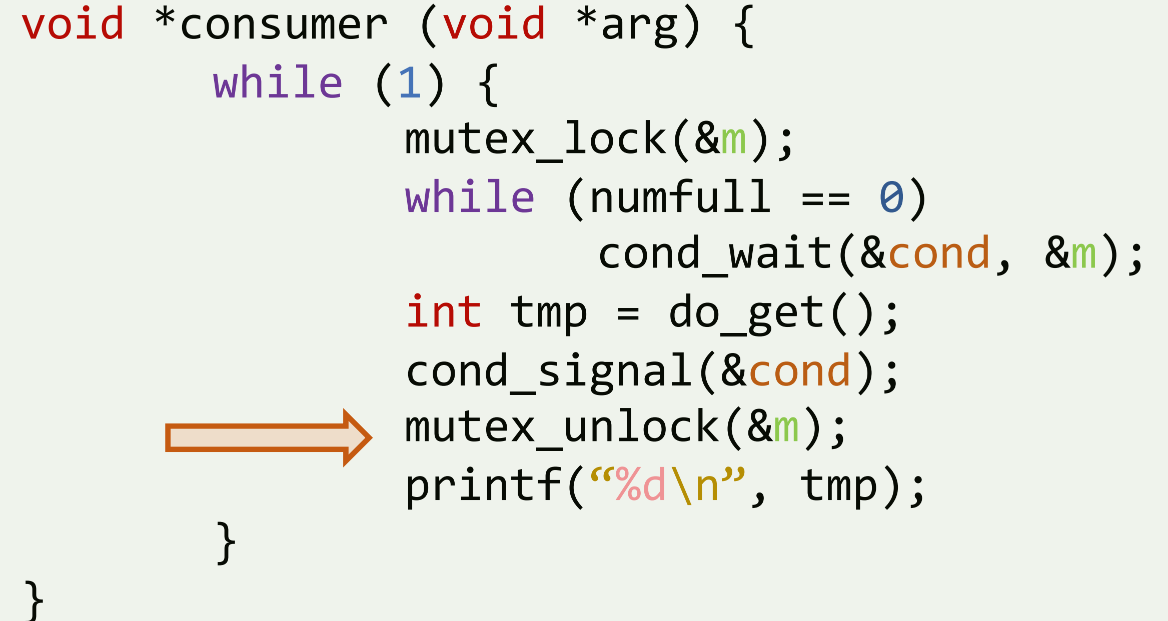

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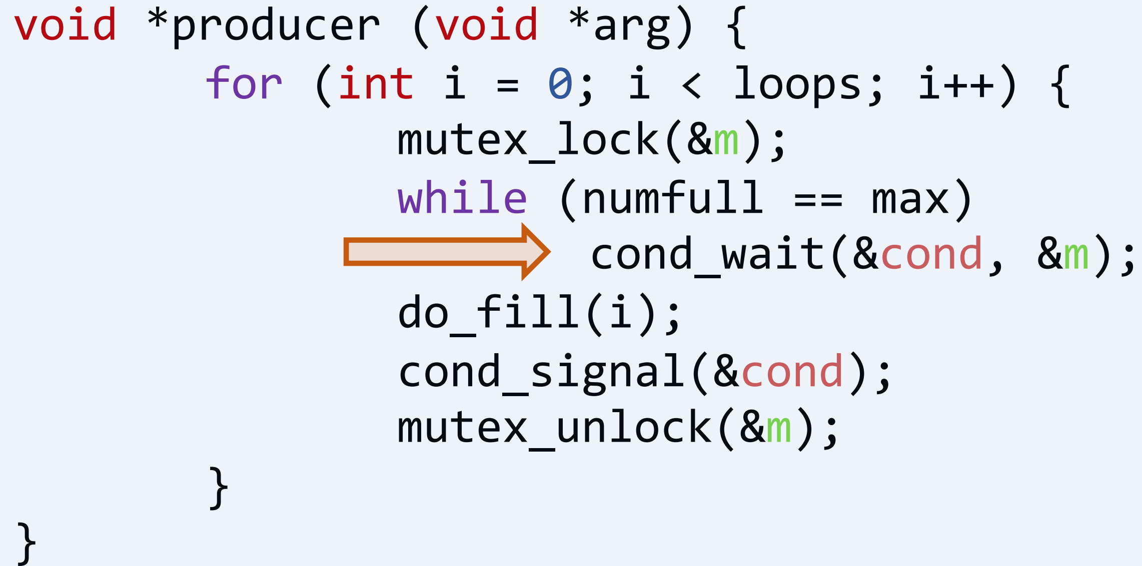

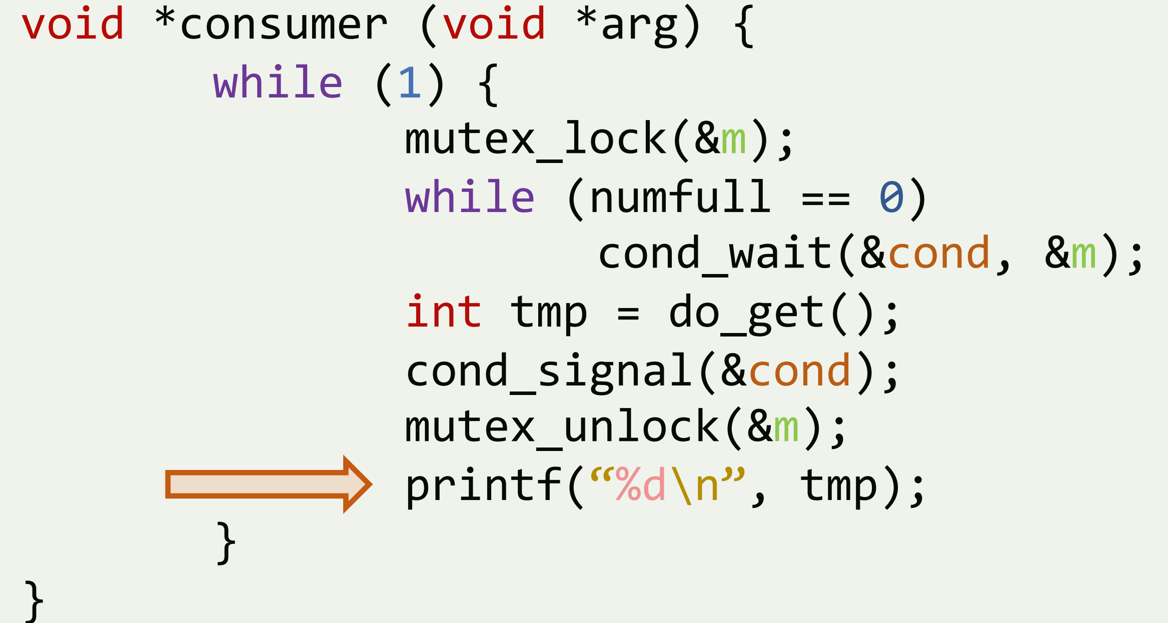

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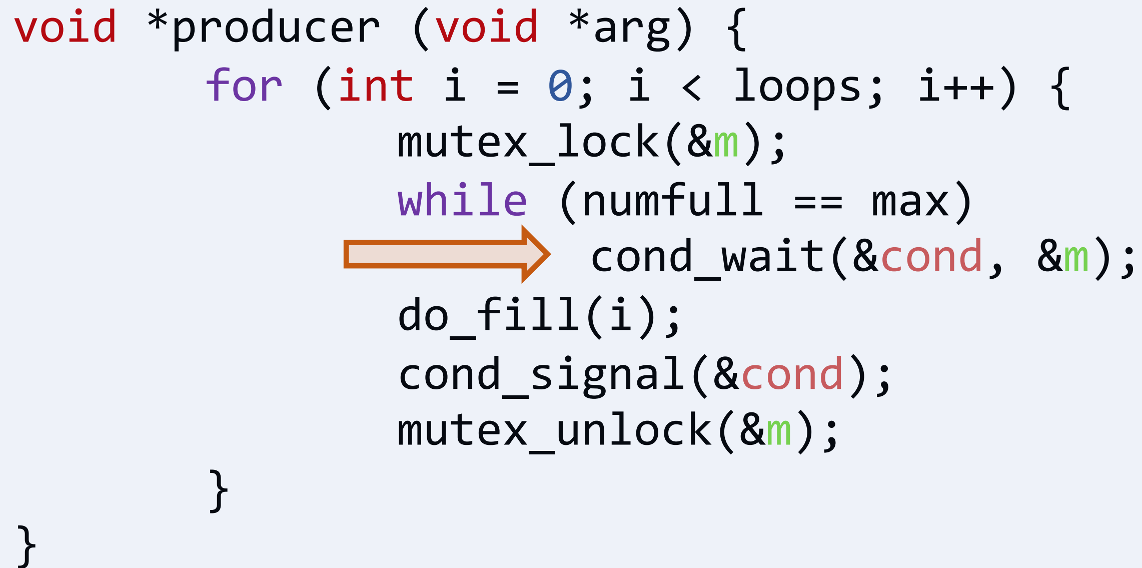

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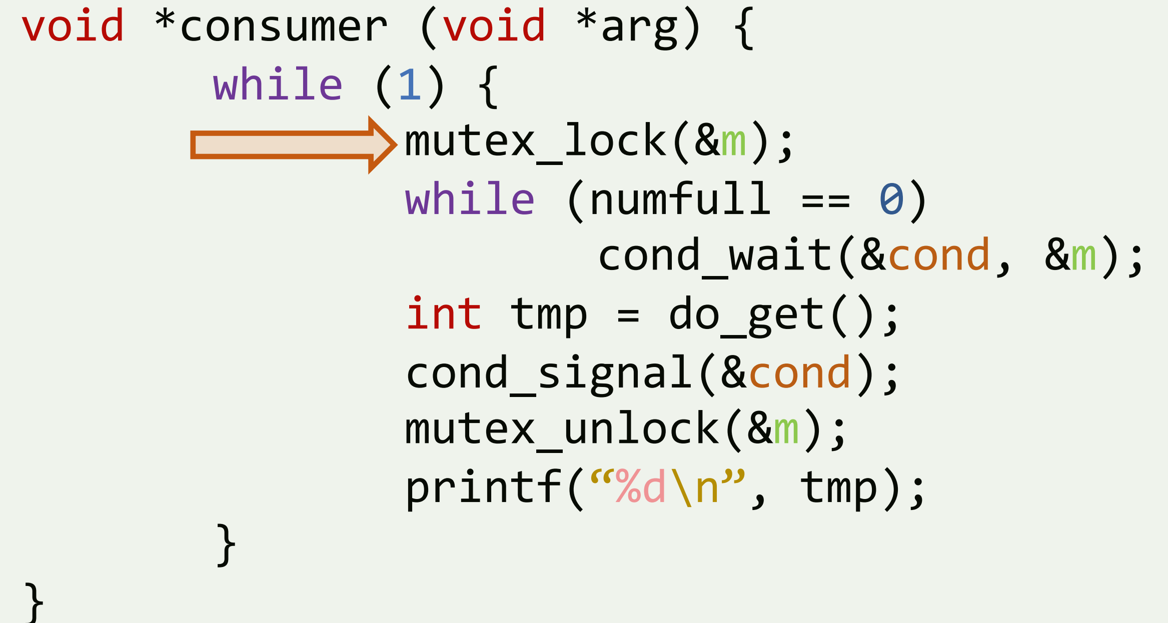

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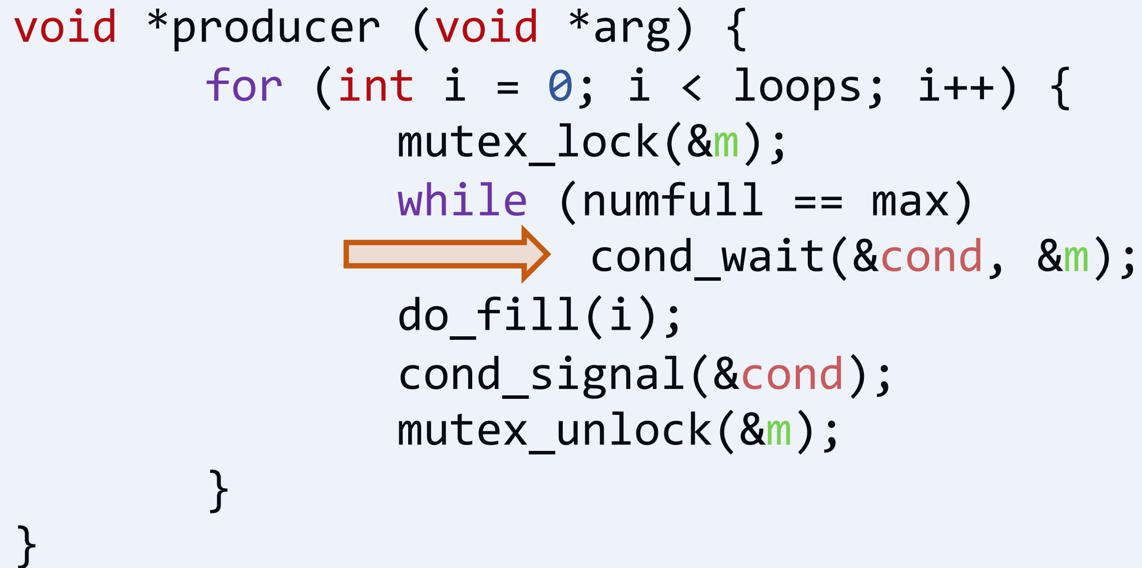

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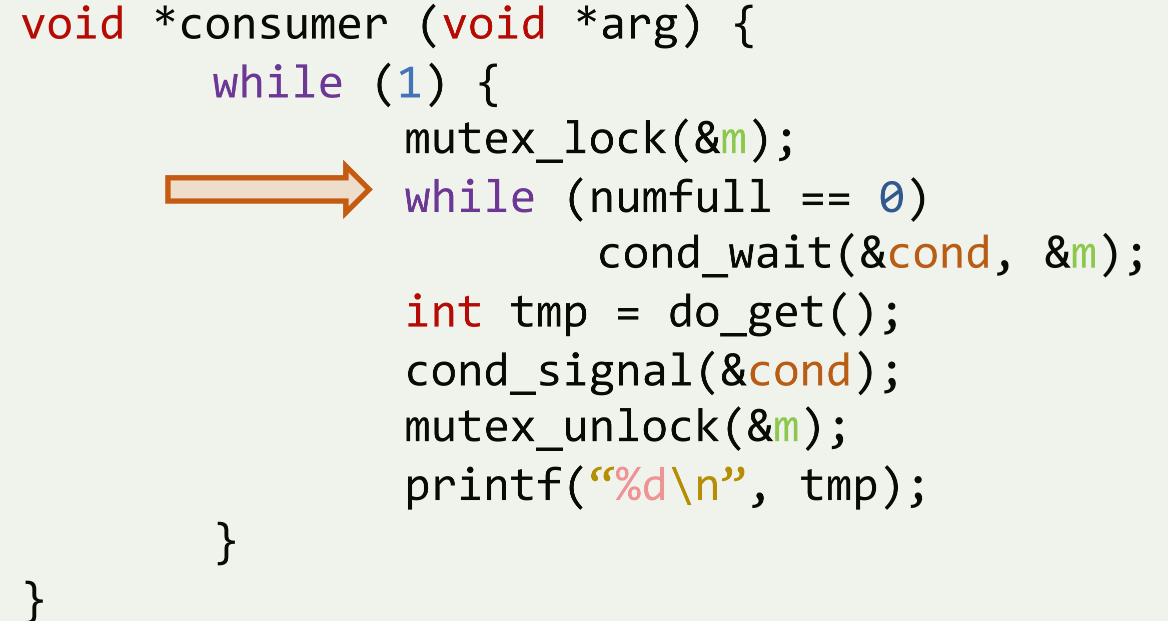

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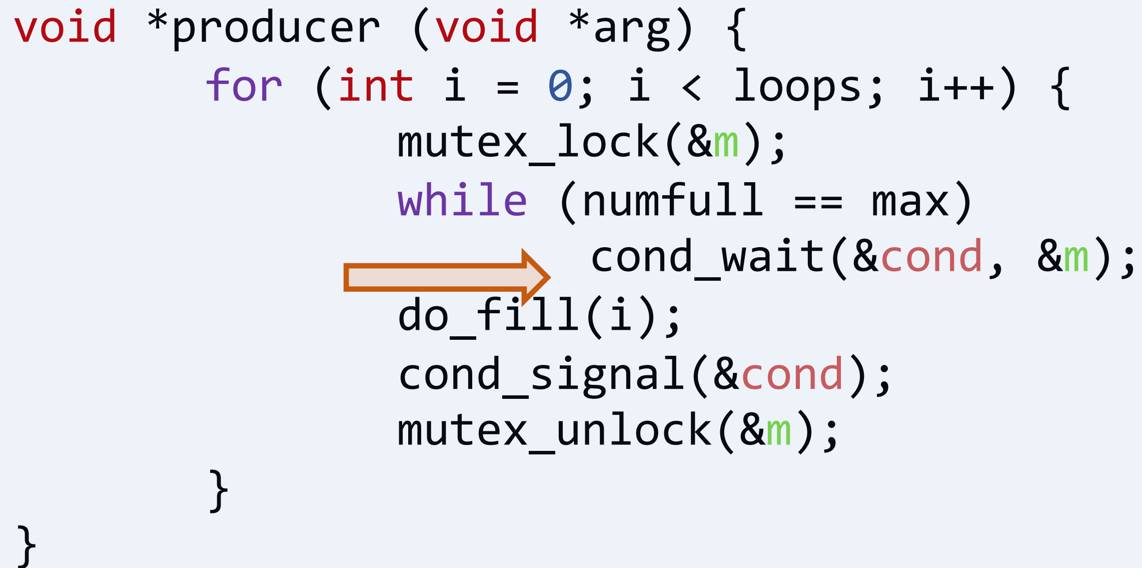

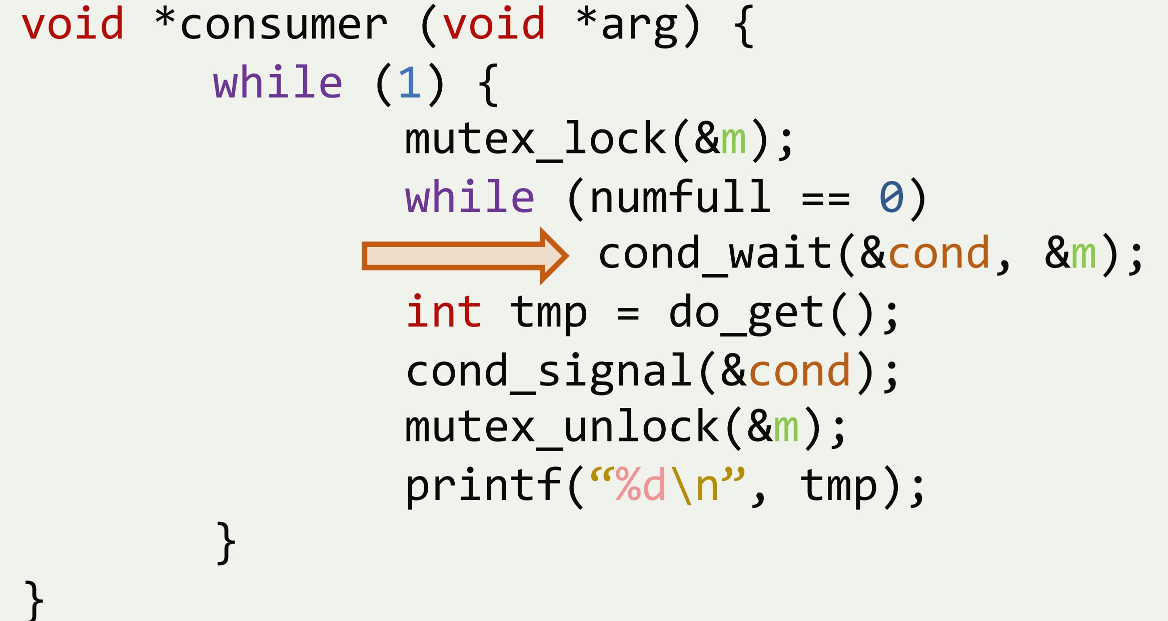

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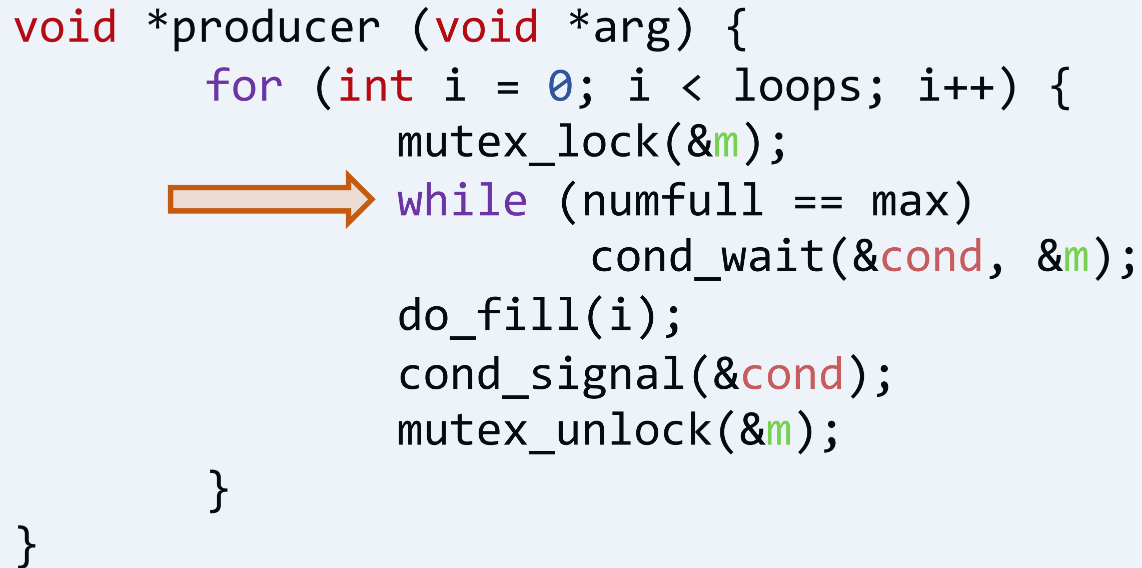

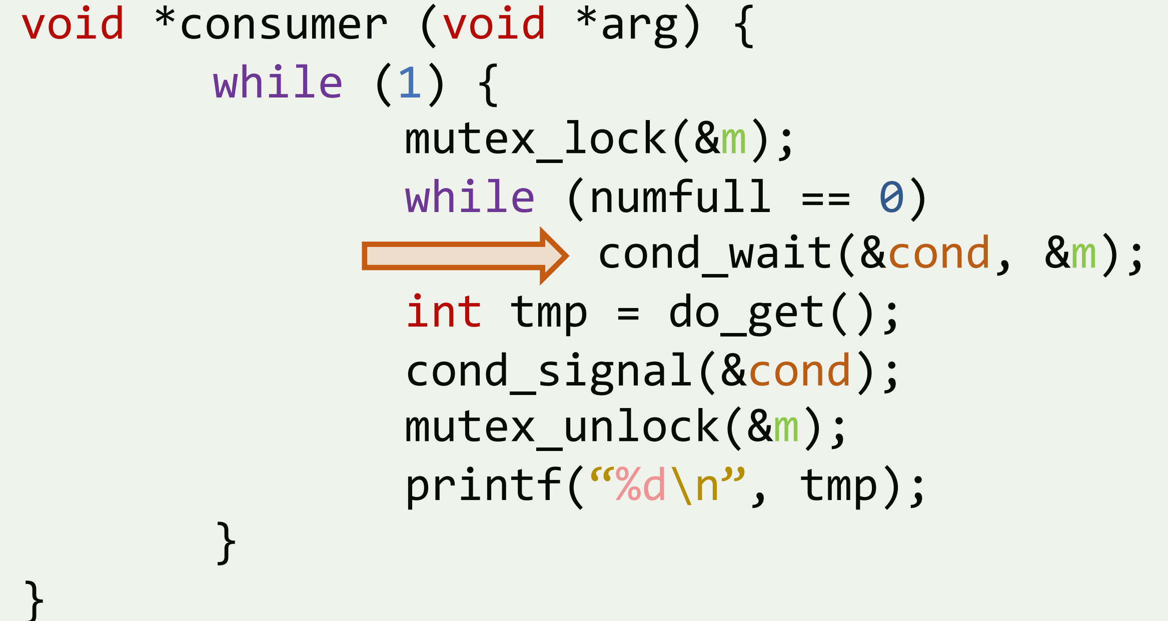

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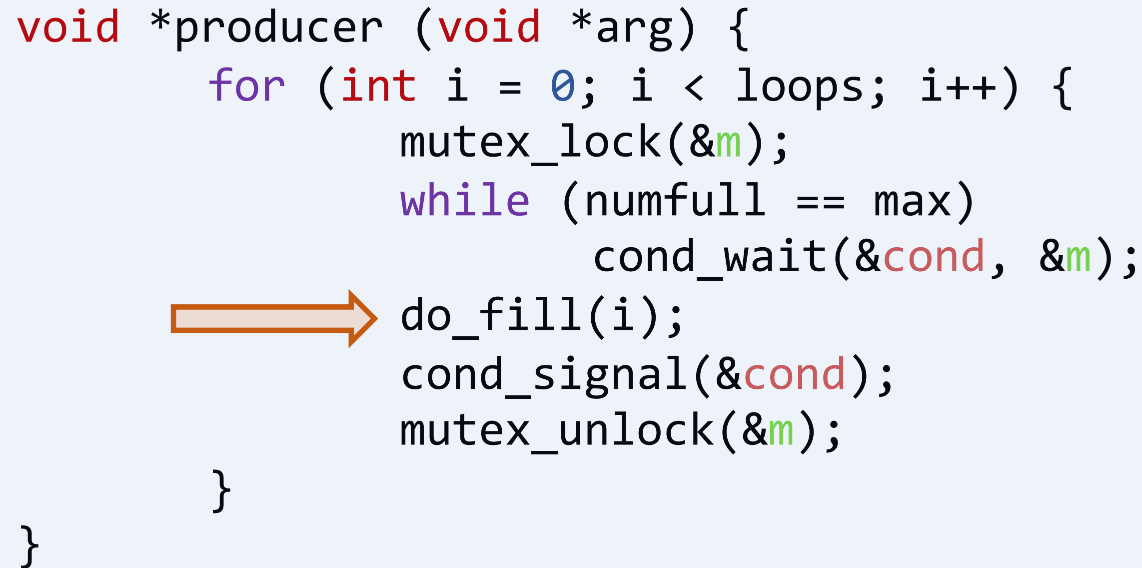
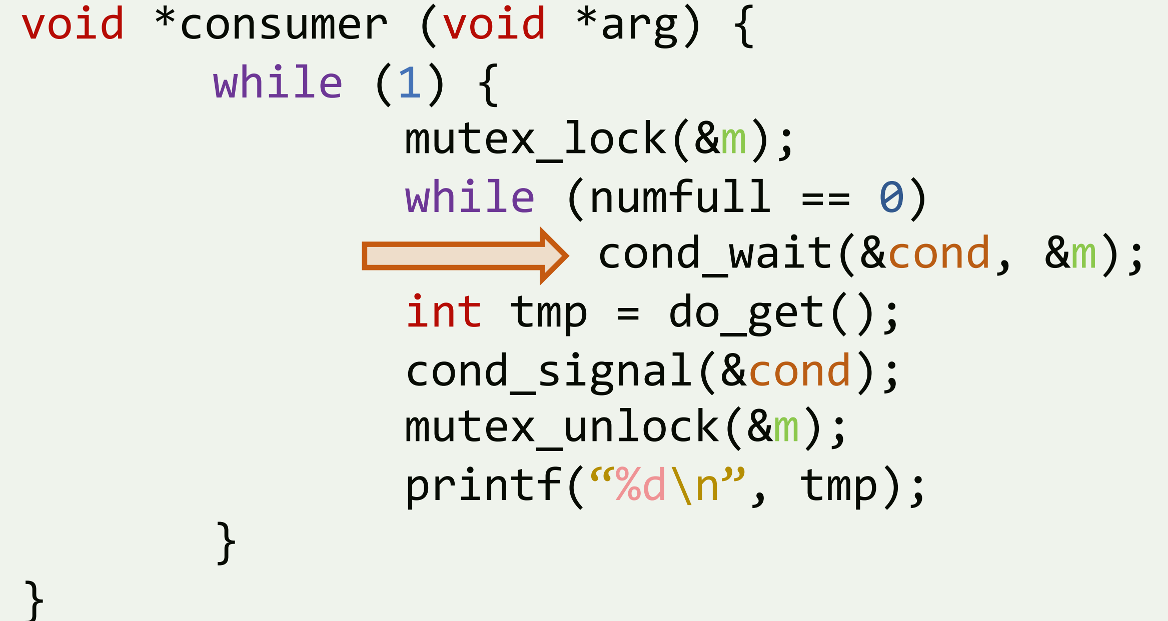
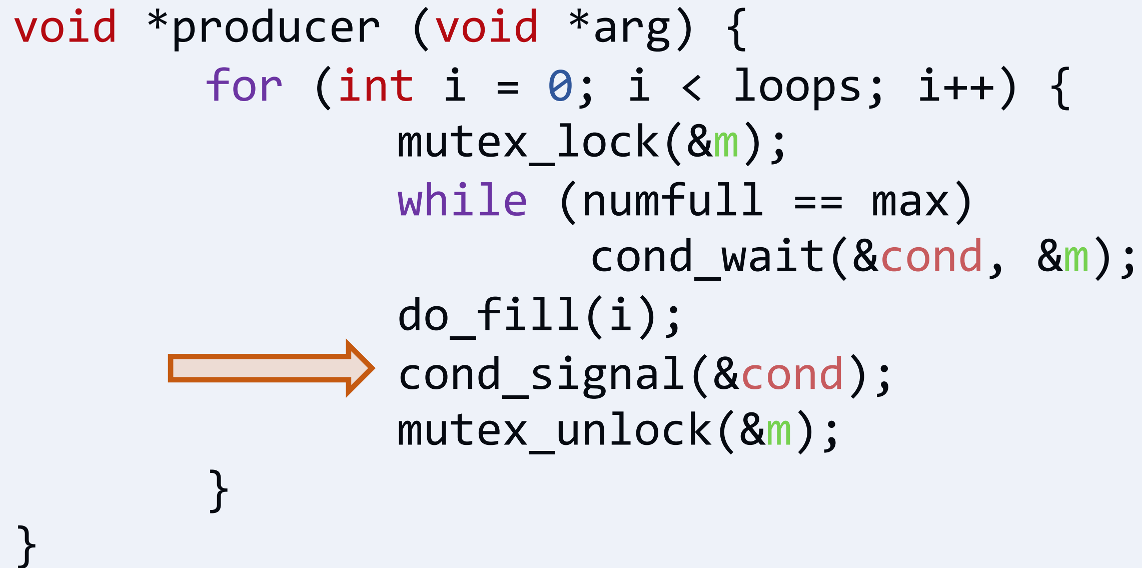
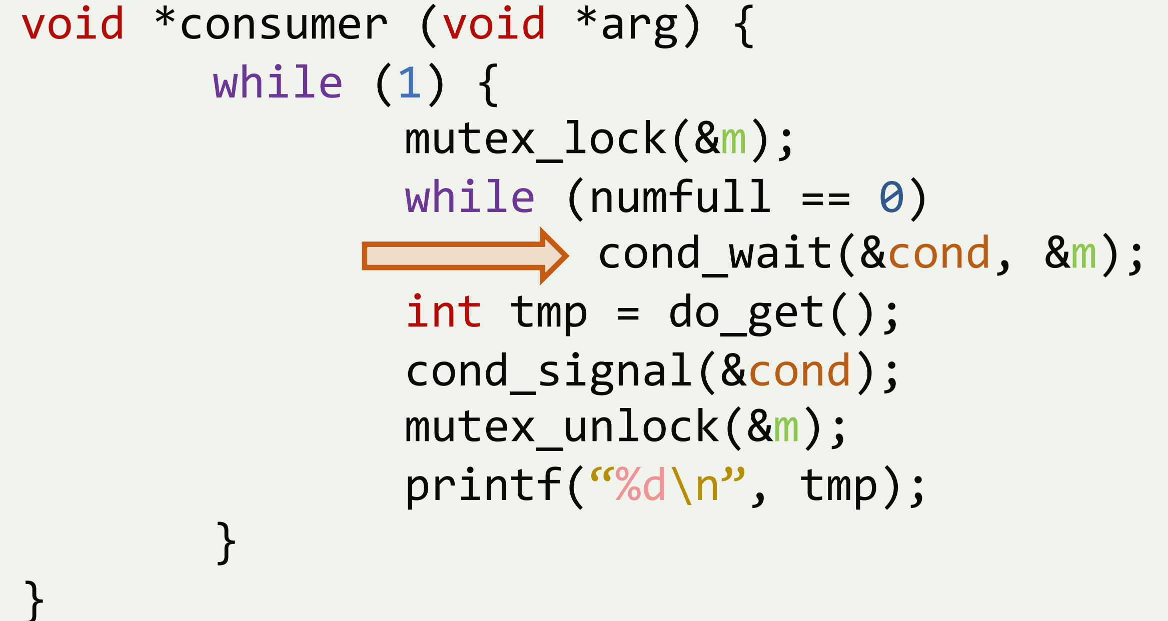


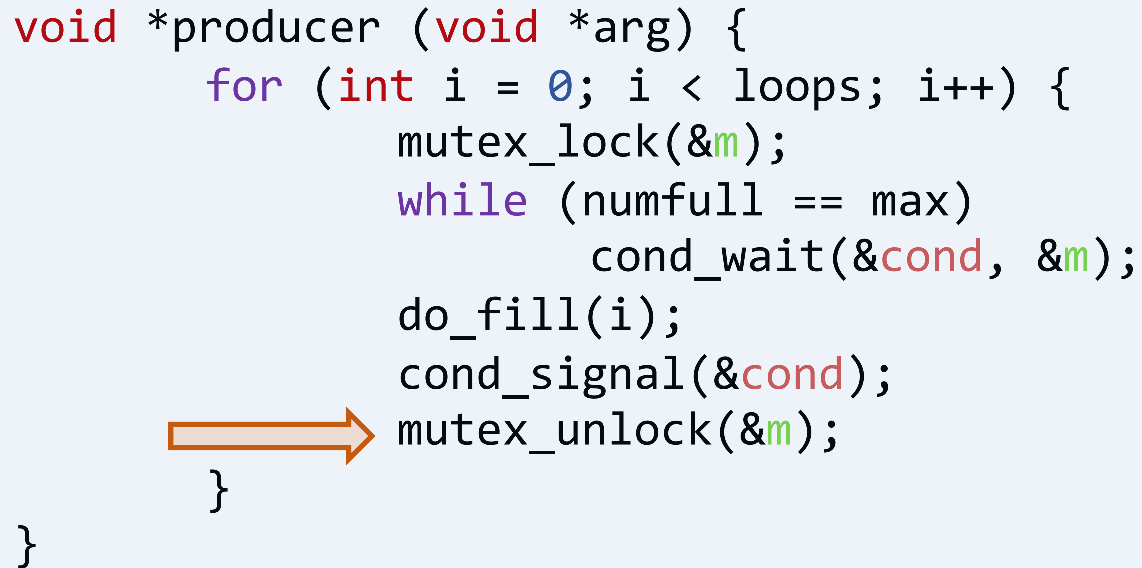


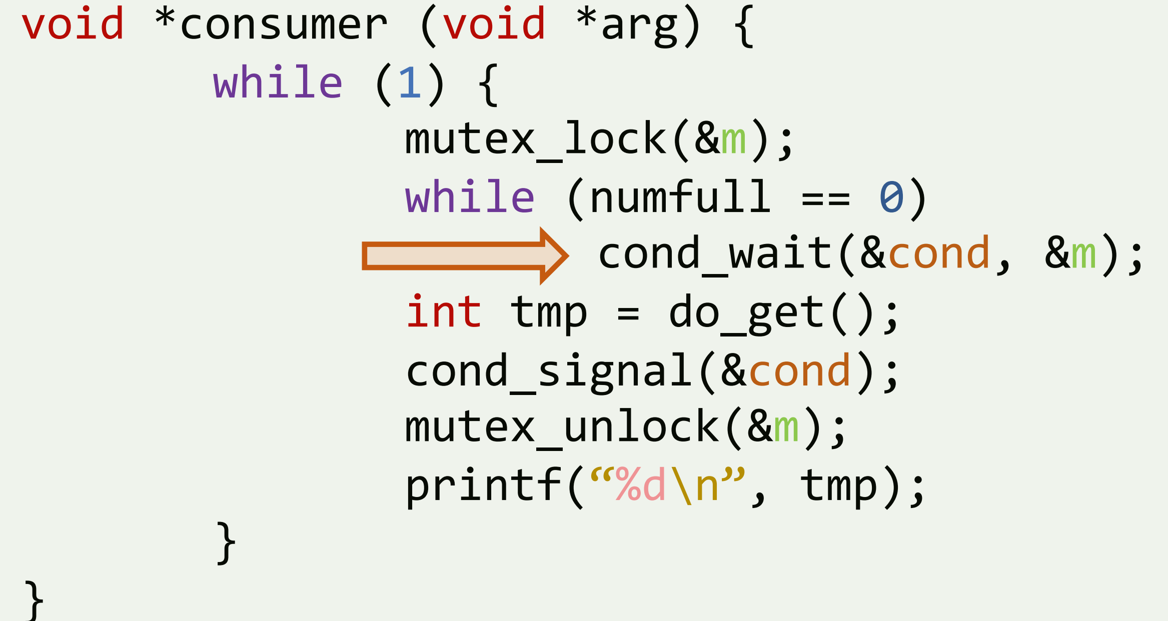
numfull = 1





numfull = 1





What about two consumers?

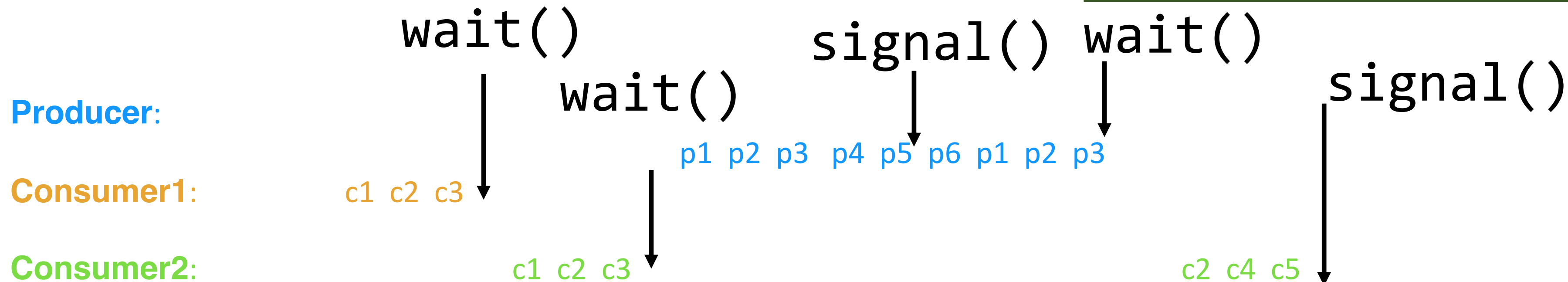
- Can you find a ***bad schedule***?

[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
        }
}
```



does last signal wake producer or consumer1?

How to wake the right thread?

- One solution:
  - wake all threads!

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

Summary

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