Synchronization

***Throughout the course we will use overheads that were adapted from those distributed from the textbook website. Slides are from the book authors, modified and selected by Jean Mayo, Shuai Wang and C-K Shene.**

If you want more effective programmers,
you will discover that they should not waste their time debugging,
they should not introduce the bugs to start with.

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Spring 2019

Synchronization Motivation

- When threads concurrently read/write shared memory, program behavior is undefined
  - Two threads write to the same variable; which one should win?
- Thread schedule is non-deterministic
  - Behavior changes when re-run program
- Compiler/hardware instruction reordering
- Multi-word operations are not atomic

Three Reasons: 1/4

- **Program execution depends on the possible interleaving of threads' access to shared data.**
  - **You learned in Concurrent Computing that this is the main cause of race conditions.**
  - **Depending on the execution order, the result of the shared data may become unpredictable.**

Three Reasons: 2/4

- **Program execution can be nondeterministic.**
- **Interrupts can happen any time and anywhere. As a result, a thread can be switched out of the CPU by the scheduler in an unpredictable way.**
  - **A multithreaded program can potentially have different interleaving execution every time when it runs.**
  - **Jim Gray in his 1998 ACM Turing Award talk coined the term *Heisenbugs* for bugs that disappear or change behavior when you try to examine them. *Bohr bugs* are deterministic and general much easier to diagnose.**

Three Reasons: 3/4

- **Compilers and processor hardware can reorder instructions.**
- **Modern compilers and hardware reorder instructions to improve performance.**
- **For higher-level language statements that are "independent" of each other, compilers are free to order the execution of these statements. Only those statements that are dependent of each other are executed in the needed order. For example, `c = a+b; x = c*100;` will be executed in the specified order. However, `c = a+b; x = m*n;` are not guaranteed to be executed in the specified order.**

Three Reasons: 4/4

Thread 1

```
p = someComputation();
pInitialized = true;
```

Thread 2

```
while (!pInitialized)
      ;
q = someFunction(p);
if (q != someFunction(p))
      panic
```

Because these two statements are independent of each other, compiler or hardware may execute the second statement prior to the first.

Suppose the order or the two statements in Thread 1 are changed.

Before the value of `p` is obtained properly, Thread 2 could start its execution.

In this case, Thread 2 could use an unexpected value of `p` to compute `q`.

Too Much Milk Example: 1/6

- Alice and Bob are sharing an apartment. Alice arrives home in the afternoon, looks in the fridge and finds that there is no milk. So, she leaves for the grocery to buy milk.
- After she leaves, Bob arrives, he also finds that there is no milk and goes to buy milk.
- At the end both buy milk and end up with too much milk.

Time	*Alice*	*Bob*
5:00	Arrive home	
5:05	Look in fridge; no milk	
5:10	Leave for grocery	
5:15		Arrive home
5:20		Look in fridge; no milk
5:25	Buy milk	Leave for grocery
5:30	Arrive home; put milk in fridge	Buy milk
5:40		Arrive home; put milk in fridge
	Too much milk	

Too Much Milk Example: 2/6

- Alice and Bob are looking for a solution to ensure that:
  - Only one person buys milk, when there is no milk.
  - Someone always buys milk, when there is no milk.
- They will communicate by leaving (signed) notes on the door of the fridge. **Note that they do not see each other**.

Alice	Bob
if (no note) **then**	**if** (no note) **then**
if (no milk) **then**	**if** (no milk) **then**
leave note	leave note
buy milk	buy milk
remove note	remove note
end if	**end if**
end if	**end if**

What if Alice and Bob come home at the same time?

Too Much Milk Example: 3/6

- Each of Alice and Bob first leaves note, checks the other's note. If no note, checks whether there is milk. If there is no milk, then busy milk. Finally, remove his/her own note.
- **Note that they do not see each other**.

Alice	Bob
`leave note` **Alice**	`leave note` **Bob**
if `(no note` **Bob**`)` **then**	**if** `(no note` **Alice**`)` **then**
if `(no milk)` **then**	**if** `(no milk)` **then**
`buy milk`	`buy milk`
end if	**end if**
end if	**end if**
`remove note` **Alice**	`remove note` **Bob**

What if Alice and Bob come home and leave note at the same time? **No milk!**

Too Much Milk Example: 4/6

- Bob leaves note and repeatedly check Alice's note until Alice's note is not on fridge.
- Once Bob finds Alice's note is not there, he check for milk. If there is no milk, Bob buys milk.
- **Note that they do not see each other.**

asymmetric!

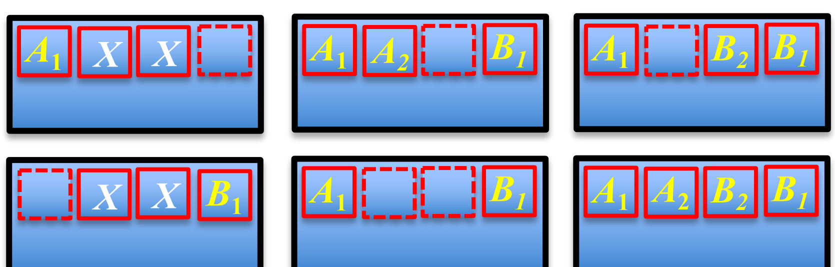
Alice	Bob
leave note **Alice**	leave note **Bob**
if (no note **Bob**) **then**	**while** (note **Alice**) **do**
	nothing;
if (no milk) **then**	**if** (no milk) **then**
buy milk	buy milk
end if	**end if**
end if	
remove note **Alice**	remove note **Bob**

We have to assume: between the time Alice removes her note, and the time she leaves a new note next time, Bob must be able to find out that Alice's note has been removed. Without this assume, they never buy milk. **Find an execution for this scenario.**

Too Much Milk Example: 5/6

- The fridge has four slots for posting notes. Alice uses A_1 and A_2, and Bob uses B_1 and B_2.
- If Alice (resp., Bob) finds that there is no note labelled B_1 (resp., A_1) on the fridge's door, then it is Alice (resp., Bob) responsibility to buy milk.
- Otherwise, when both A_1 and B_1 are present, a decision is made according to the notes A_2 and B_2.
- If both A_2 and B_2 are present or if neither of them is present than it is Bob's responsibility to by milk.
- Otherwise, it is Alice's responsibility.

The six possible configurations of the notes on the fridge's door



Alice's turn

Bob's turn

Too Much Milk Example: 6/6

- The fridge has four slots for posting notes. Alice uses A_1 and A_2, and Bob uses B_1 and B_2.
- **This is a correct solution. Study and prove it.**

Alice

```
leave note A1
if (B2) then
   leave note A2
else
   remove note A2
end if /* Alice gives priority */
       /* to Bob in buying milk*/
while B1 and
   ((A2 and B2) or
   (no A2 and no B2)) do
      nothing;
if (no milk) then
   buy milk
end if
remove note A1
```

Bob

```
leave note B1
if (no A2) do
   leave note B2
else
   remove note B2
end if /* giving to Alice */

while A1 and
   ((A2 and no B2) or
   (no A2 and B2)) do
      nothing;
if (no milk) then
   buy milk
end if
remove note B1
```

Lessons

- Solution is complicated
  - "obvious" code often has bugs
- You may replace Alice and Bob with two computers and the fridge with a file.
- Modern compilers/architectures reorder instructions
  - Making reasoning even more difficult
- Generalizing to many threads/processors
  - Even more complex: see Peterson's algorithm

Definitions

Race condition: output of multiple threaded program that manipulates a shared resource concurrently depends on the order of operations among threads

Mutual exclusion: only one thread does a particular thing at a time

- **Critical section**: piece of code that only one thread can execute at once

Lock: prevent someone from doing something

- Lock before entering critical section, before accessing shared data
- Unlock when leaving, after done accessing shared data
- Wait if locked (all synchronization involves waiting!)

Roadmap

Concurrent apps built using shared objects.

Shared objects built using synchronization variables

Synchronization variables (often) built using atomic instructions

Concurrent Applications

Shared Objects

Bounded Buffer   Barrier

Synchronization Variables

Semaphores   Locks   Condition Variables

Atomic Instructions

Atomic and act as memory barrier

Interrupt Disable   Test-and-Set

Hardware

Multiple Processors   Hardware Interrupts

Locks

- `Lock::acquire`
  - Wait until lock is free, then take it
- `Lock::release`
  - Release lock, waking up anyone waiting for it

1. At most one lock holder at a time (Mutual exclusion)
2. If no one holding, acquire gets lock (Progress)
3. If all lock holders finish and no higher priority waiters, waiter eventually gets lock
   - Need not be FIFO!

Properties of a solution to the "Critical Section" problem

Question: Why only Acquire/Release

- Suppose we add a method to a lock, to ask if the lock is free.   Suppose it returns true. Is the lock:
  - Free?
  - Busy?
  - Don't know?

  when testing the return value

In security lingo, leads to a *TOCTOU error*. "Time of check to time of use"

Lock Example: malloc/free

```
char *malloc (n) {
    heaplock.acquire();
    p = allocate memory
    heaplock.release();
    return p;
}
```

```
void free(char *p) {
    heaplock.acquire();
    put p back on free list
    heaplock.release();
}
```

Rules for Using Locks

- Lock is initially free
- Always acquire before accessing shared data structure.
- Always release after finishing with shared data
  - End of procedure!
  - Only the lock holder can release
  - **DO NOT** throw lock for someone else to release
- Never access shared data without lock
  - Danger!
- Don’t put shared objects on the stack. **Why?**

Will this code work? 1/2

`p` is a shared variable

```
if (p == NULL) {
        lock.acquire();
        if (p == NULL) {
            p = newP();
        }
        lock.release();
}
use p->field1
```

```
newP()
{
   p = malloc(sizeof(p));
      p->field1 = …
      p->field2 = …
      return p;
}
```

Will this code work? 2/2

Thread 1	Thread 2
`1. if (p == NULL) {`	
`2.     lock.acquire();`	
`3.     if (p == NULL) {`	
`4.         p = malloc(..);`	
	`1. if (p == NULL) { }`
	`2. p->field1;`
`        p->field1;`	
`        p->field2;`	
`6.     lock.release();`	
`8. p->field1;`	

```
1. if (p == NULL) {
2.       lock.acquire();
3.       if (p == NULL) {
4.           p = newP();
5.       }
6.       lock.release();
7. }
8. use p->field1
```

```
lock.acquire();
    if (p == NULL) {
        p = newP();
    }
lock.release();
```

ATOMIC WRT T_B

```
lock.acquire();
    if (p == NULL) {
        p = newP();
    }
lock.release();
```

ATOMIC WRT T_A

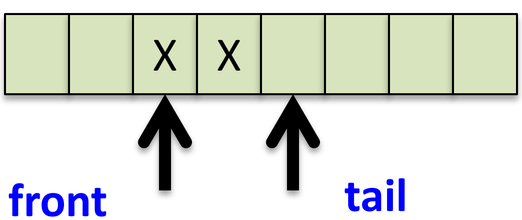
Example Shared Object Using Locks
Bounded Buffer

```
int front = .., tail = …;
```

```
tryget() {
  item = NULL;
  lock.acquire();
  if (front < tail) {
    item = buf[front%MAX];
        front++;
  }
  lock.release();
  return item;
}
```

```
tryput(item) {
  lock.acquire();
  if ((tail–front) < size) {
    buf[tail % MAX] = item;
    tail++;
  }
  lock.release();
}
```

Initially: front = tail = 0; lock = FREE; MAX is buffer capacity



front < tail => data available
tail = front + size => full

The Milk Problem Revisited

- Alice and Bob calls `BuyMilkIfNeeded()` to determine whether she or he should buy milk.
- Prove that
  - Only one person buys milk when there is no milk
  - Someone always buys milk when there is no milk

```
BuyMilkIfNeeded()
{
    lock.acquire();
    if (no milk) {
        buy milk;
    }
    lock.release();
}
```

Buying milk is mutually exclusive, because only one person should buy.

Both have to check "milk" in a mutually exclusive way.
If no milk, then buy it!

Can "buy milk" be moved outside of the critical section?

Condition Variables

- Waiting inside a critical section
  - Called only when holding a lock
- Operations
  - **Wait** - atomically release lock and relinquish processor
    - Reacquire the lock when wakened
  - **Signal** - wake up a waiter, if any
  - **Broadcast** - wake up all waiters, if any

Not UNIX `wait()` and `signal()`

Mesa vs. Hoare semantics

- Mesa
  - Signal puts waiter on ready list
  - Signaler keeps lock and processor
- Hoare
  - Signal gives processor and lock to waiter
  - When waiter finishes, processor/lock given back to signaler
  - Nested signals possible (i.e., cascading release)!

Hoare vs. Mesa: 1/2

Producer

```
mutex::acquire();
  if (count >= MAX)
     wait(notFull, mutex);
  buf[count]='a';
  count++;
  signal(notEmpty);
Mutex::release();
```

Consumer

```
mutex::acquire();
  if (count == 0)
     wait(notEmpty, mutex);
  ch=buf[count];
  count--;
  signal(notFull);
Mutex::release;
```

Replace the `if` with a `while` for the Mesa type

What if the above code is run under the Mesa type? Problem!!!

Hoare vs. Mesa: 2/2

buffer size = 2

P_1	P_2	P_3	P_4	C_1	Count
					0
Add 1 item					1
	Add 1 item				2
		`acquire`			2
		`wait`			2
				`acquire`	2
				Take 1 item	1
				`signal`	1
				`release`	1
			Add 1 item		2
		No space!			2

Under Hoare, P_3 should immediately get the critical section

By the time P_3 gets the monitor and runs again, the free spot has already been taken by P_4.

Under Mesa the signaler continues

Condition Variable Design Pattern

```
methodThatWaits() {
   lock.acquire();
   // Read/write shared state

   while (!testSharedState()) {
         cv.wait(&lock);
   }

   // Read/write shared state
   lock.release();
}
```

```
methodThatSignals() {
   lock.acquire();
   // Read/write shared state

   // If testSharedState now true
   cv.signal(&lock);


   // Read/write shared state
   lock.release();
}
```

Assume signaler keeps lock. More later.

Give up lock and reacquire!!

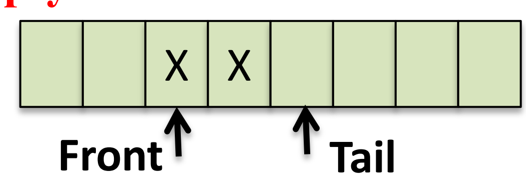
Example: Bounded Buffer

```
get() {
  lock.acquire();
  while (front == tail) {
    empty.wait(lock); /* Don't know
                         state here */
  }  // Not empty; front != tail
  item = buf[front % MAX];
  front++;
  full.signal(lock);   // Not full
  lock.release();// Front <= tail
  return item;
}
```

```
put(item) {
  lock.acquire();
  while ((tail – front) == MAX) {
    full.wait(lock);
  }  // Not full; tail != front+MAX

  buf[tail % MAX] = item;
  tail++;
  empty.signal(lock);   // Not empty
  lock.release(); // Front+MAX>=tail
}
```

Initially: front = tail = 0; MAX is buffer capacity
empty/full are condition variables



Front = Tail => Empty
Tail = Front + SIZE => Full

Pre/Post Conditions

- What is state of the bounded buffer at lock acquire?
  - `front <= tail`
  - `front + MAX >= tail` (wraparound)
- These are also true on return from wait
- And at lock release
- Allows for proof of correctness

Otherwise, wrote to full buffer or read from empty buffer

Pre/Post Conditions

```
methodThatWaits() {
    lock.acquire();
    // Pre-condition: State is
    // consistent

    // Read/write shared state

    while (!testSharedState()) {
        cv.wait(&lock);
    }
    // WARNING: shared state may
    // have changed!  But
    // testSharedState is TRUE
    // and pre-condition is true
    //(just got the lock)

    // Read/write shared state
    lock.release();
}
```

```
methodThatSignals() {
    lock.acquire();
    // Pre-condition: State is
    // consistent

    // Read/write shared state

    // If testSharedState is
    // now true
    cv.signal(&lock);

    // NO WARNING: signal keeps
    // lock

    // Read/write shared state
    lock.release();
}
```

Condition Variables

- **MUST** hold lock when calling wait, signal, broadcast
  - Condition variable is sync FOR shared state
  - **ALWAYS** hold lock when accessing shared state
- Condition variable is memoryless
  - If signal when no one is waiting, no op
  - If wait before signal, waiter wakes up
- Wait atomically releases lock

Condition Variables, cont'd

- When a thread is woken up from wait, it may or may not run immediately
  - **signal**/**broadcast** put thread on a waiting list to "re-enter" the critical section
  - When lock is released, anyone might acquire it
- Wait **MUST** be in a loop

```
while (needToWait()) {
      condition.Wait(lock);
}
```

- Simplifies implementation
  - Of condition variables and locks
  - Of code that uses condition variables and locks

Design of Shared Objects

- Identify objects or data structures that can be accessed by multiple threads concurrently
- Add locks to object/module
  - Grab lock on start to every method/procedure and release lock on finish
- If need to wait
  - `while(needToWait()) { condition.Wait(lock); }`
  - Do not assume when you wake up, signaler ran
- If do something that might wake someone up
  - Signal or Broadcast
- Always leave shared state variables in a consistent state
  - When lock is released, or when waiting

Implementation Best Practices

- Use consistent structure
- Always use locks and condition variables
- Always acquire lock at beginning of procedure, release at end
- Always hold lock when using a condition variable
- Always wait in while loop

```
lock()
 . . . ops . . .
while (testState()){sleep();}
 . . . ops . . .
release()
```

Still holding the lock!

```
lock()
 . . . ops . . .
release()
while (testState()){sleep();}
lock()
 . . . ops . . .
release()
```

State may change between end of loop and lock()

Implementing Synchronization

Approach 1 : Using memory load/store

- See too much milk solution/Peterson's algorithm

Approach 2:

```
Lock::acquire()
    { disable interrupts }
Lock::release()
    { enable interrupts }
```

```
Thread 1: aLock.acquire();
               while (1==1);
          aLock.release();
```

Interrupts are disabled.
How to regain control?

Only possible in kernel;
Could never let a user process run with interrupts off!

Lock Implementation: Uniprocessor

```
Lock::acquire() {
  disableInterrupts(); /* mem barrier */
  if (value == BUSY) {
    waiting.add(myTCB);
    myTCB->state = WAITING;
    next = readyList.remove();
    switch(myTCB, next);
    myTCB->state = RUNNING;
  }
  else {
    value = BUSY;
  }
  enableInterrupts(); /* mem barrier */
}
```

queue of threads waiting on this lock

switch to another thread control will not return until it is released by lock::release

awaken with lock; still BUSY

```
Lock::release() {
  disableInterrupts();
  if (!waiting.Empty()) {
    next = waiting.remove();
    next->state = READY;
    readyList.add(next);
  }
  else {
      value = FREE;
  }
  enableInterrupts();
}
```

Multiprocessor

- Interrupts turned off at individual processors
  - No instruction to turn them off on all processors simultaneously
  - Threads may be running on different processors
- Read-modify-write instructions
  - Atomically read a value from memory, operate on it, and then write it back to memory
  - Intervening instructions prevented in hardware
- Examples
  - Test and set, Compare and swap
  - Intel: xchg, lock prefix
- Any of these can be used for implementing locks and condition variables!

Spinlocks

A spinlock is a lock where the processor waits in a loop for the lock to become free

- Assumes lock will be held for a short time
- Used to protect the CPU scheduler and to implement locks

Busy wait. Reasonable for short hold, e.g. < time for context switch

```
Spinlock::acquire() {
   while (testAndSet(&lockValue) == BUSY)
      ;
}
Spinlock::release() {
   lockValue = FREE;
   memorybarrier();
}
```

Executed ATOMICALLY:

```
bool testAndSet(bool *flag){
    bool old=*flag;
    *flag=BUSY;
    return old;  // if FREE,  return FREE
                 // Next process through sees
                 // and returns BUSY
}
```

Memory operations before barrier guaranteed to be performed

What Thread Is Currently Running?

- Thread scheduler needs to find the TCB of the currently running thread
  - To suspend and switch to a new thread
  - To check if the current thread holds a lock before acquiring or releasing it
- On a uniprocessor, easy: just use a global
- On a multiprocessor, various methods:
  - Compiler dedicates a register (e.g., r31 points to TCB running on the this CPU; each CPU has its own r31)
  - If hardware has a special per-processor register, use it
  - Fixed-size stacks: put a pointer to the TCB at the bottom of its stack
    - ✓ Find it by masking the current stack pointer

Lock Implementation: Multiprocessor 1/2

```
Lock::acquire() {
    spinLock.acquire();
    /* Protects lock state */
    if (value == BUSY) {
        waiting.add(myTCB);

    scheduler.suspend(&spinLock);
    }
    else {
        value = BUSY;
    }
    spinLock.release();
}
```

```
Lock::release() {
    spinLock.acquire();
    if (!waiting.Empty()) {
        next = waiting.remove();

    scheduler.makeReady(next);
    } else {
      value = FREE;
    }
    spinLock.release();
}
```

scheduler releases spinlock (next slide)

scheduler makes the new one ready (next slide)

Lock Implementation: Multiprocessor 2/2

```
scheduler::suspend(SpinLock *lock)
{
  TCB *next;

  disableInterrupts(); /* This processor! */
  schedSpinLock.acquire(); /*Ready list */
  lock->release();/* Lock on lock state */
  myTCB->state = WAITING;
  next = readyList.remove();
  thread_switch(myTCB, next);
  myTCB->state = RUNNING;
  schedSpinLock.release();
  enableInterrupts();
}
```

```
scheduler::makeReady(TCB *thread)
{
    disableInterrupts();
    schedSpinLock.acquire();
    readyList.add(thread);
    thread->state = READY;
    schedSpinLock.release();
    enableInterrupts();
}
```

To suspend a thread on a multiprocessor, we need to first disable interrupts to ensure the thread is not preempted while holding the ready list spinlock.

Now, it is safe to release the lock's spinlock and switch to a new thread.

New running thread

An Execution Sequence

Three locks are involved: Lock, spinLock and schedSpinLock, all initialized to FREE

Thread 1	Thread 2	Lock value	spinlock value	schedSpinLock value
Lock.acquire()		FREE	FREE	FREE
spinLock.acquire()		FREE	FREE	FREE
while (…)		FREE	BUSY	FREE
if (value==BUSY)		FREE	BUSY	FREE
value = BUSY		BUSY	BUSY	FREE
spinLock.release();		BUSY	FREE	FREE
Thread 1 has Lock				
	Lock.acquire()	BUSY	FREE	FREE
	spinLock.acquire()	BUSY	FREE	FREE
	while (…)	BUSY	BUSY	FREE
	if (value==BUSY)	BUSY	BUSY	FREE
	waiting.add(myTCB)	BUSY	BUSY	FREE
	scheduler.suspend(&spinlock)	BUSY	BUSY	FREE
	disableinterrupts	BUSY	BUSY	FREE
	schedSpinLock.acquire()	BUSY	BUSY	BUSY
	spinLock.release()	BUSY	FREE	BUSY
	myTCB->state = WAITING	BUSY	FREE	BUSY
	next = readyList.remove()	BUSY	FREE	BUSY
	thread_switch(myTCB, next)	BUSY	FREE	BUSY
Other threads run … acquire, release ready list spinlock spinLock				
	myTCB->state = RUNNING	BUSY	FREE	BUSY
	schedSpinLock.release()	BUSY	FREE	FREE
	enableinterrupts	BUSY	FREE	FREE
Other threads run and Thread 2 was switched out				

Semaphores

- **Semaphore has a non-negative integer value**
  - `P()` **atomically waits for value to become > 0, then decrements**
  - `V()` **atomically increments value (waking up waiter if needed)**
- **Semaphores are like integers except:**
  - **Only operations are** `P` **and** `V`
  - **Operations are atomic**
    - **If value is 1, two P's will result in value 0 and one waiter**
- **Semaphores are useful for**
  - **Unlocked wait: interrupt handler, fork/join**

Semaphore Bounded Buffer

```
get()
{
    fullSlots.P();
    mutex.P();
    item = buf[front%MAX];
    front++;
    mutex.V();
    emptySlots.V();
    return item;
}
```

```
put(item)
{
    emptySlots.P();
    mutex.P();
    buf[last%MAX] = item;
    last++;
    mutex.V();
    fullSlots.V();
}
```

Initially: `front = last = 0`; `MAX` is buffer capacity
`mutex = 1`; `emptySlots = MAX`; `fullSlots = 0`;

Implementing Condition Variables using Semaphores: 1

```
wait(lock) {
    lock.release();
    semaphore.P();
    lock.acquire();
}
signal() {
    semaphore.V();
}
```

CV `Wait()`: Release lock;
Wait for signal;
Reacquire lock;

CV `Signal()`: Awaken waiter, if there is one;
Otherwise, nop;

Is this solution correct? No!

What happened if a thread calls `signal()` and no one is waiting?

With condition variables, if a thread calls `signal()` 100 times, when no one is waiting, the next `wait()` call will wait.

With the above code, the next 100 threads call `wait()` will return immediately!

Implementing Condition Variables using Semaphores: 2

```
wait(lock)
{
    lock.release();
    semaphore.P();
    lock.acquire();
}
```

```
signal()
{
    if (semaphore is not empty)
        semaphore.V();
}
```

no way to access the internal of a semaphore

Thread 1	Thread 2	Semaphore	Comment
wait(lock)		0	Thread 1 calls wait(lock)
release lock		0	Release the lock, switched out
	signal()	0	Thread 2 calls signal()
	semaphore Ø	0	Thread 2 found no waiting
	exit	0	Thread 2 return from signal()
P()		0	Thread 1 waits!
Thread 1 blocks, but should have been released			

Implementing Condition Variables using Semaphores: 3

```
wait(lock)
{
   queue.Append(myTCB);
   lock.release();
   semaphore.P();
   lock.acquire();
}
```

```
signal()
{
   if (!queue.Empty()) {
      semaphore.V();
   }
}
```

Thread 1	Thread 2	Thread 3	Comment
wait()			semaphore = 0
myTCB queued			
lock released			lock is open
	semaphore V()		semaphore = 1
		wait()	
		myTCB queued	
		semaphore P()	semaphore = 0
			Thread 3 released
semaphore P()			

Because no one is waiting,
this signal() should have no effect.
But, this signal() has an impact on
a later thread. Incorrect implementation.

thread 2 should
release thread 1

thread 2 releases thread 3

Implementing Condition Variables using Semaphores: 4

```
wait(lock) {
    semaphore = new Semaphore(0); // each waiting threads
                                  //   has its own semaphore
    queue.Append(semaphore);      // queue of waiting threads
    lock.release();
    semaphore.P();
    lock.acquire();
}
signal() {
    if (!queue.Empty()) {
        semaphore = queue.Remove();
        semaphore.V();       // wake up waiter associated
                             //   with semaphore
    }
}
```

Create a semaphore for each waiter. Signaller awakens specific thread.

Remember the rules

- Use consistent structure
- Always use locks and condition variables
- Always acquire lock at beginning of procedure, release at end
- Always hold lock when using a condition variable
- Always wait in while loop
- Never spin in `sleep()`

The End