Synchronization 2: Monitors and Language Support for Concurrency

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CS 162: Operating Systems and System Programming

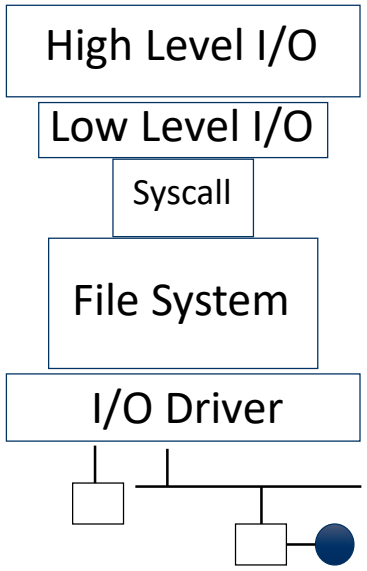
Lecture 9

https://inst.eecs.berkeley.edu/~cs162/su20

Read: A&D 5.4-6

Recall: Layers…

Application / Service



User App

```
length = read(input_fd, buffer, BUFFER_SIZE);
```

User Library

```
ssize_t read(int, void *, size_t){
   marshal args into registers
   issue syscall
   register result of syscall to rtn value
};
```

Exception U→K, interrupt processing

```
void syscall_handler (struct intr_frame *f) {
   unmarshall call#, args from regs
   dispatch : handlers[call#](args)
   marshal results fo syscall ret
}
```

```
ssize_t vfs_read(struct file *file, char __user
*buf, size_t count, loff_t *pos)
{
     User Process/File System relationship
    call device driver to do the work
}
```

Device Driver

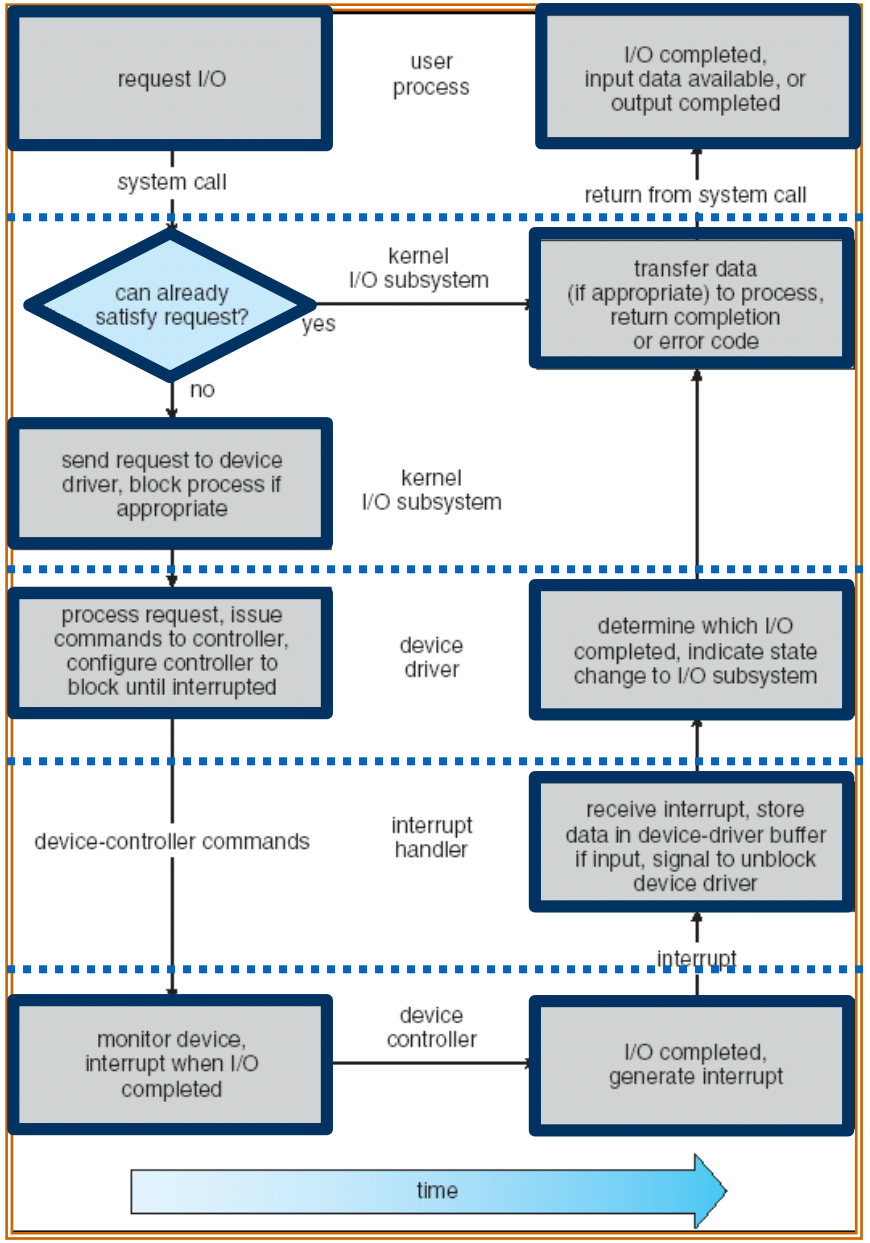
User Program

Kernel I/O Subsystem

Device Driver Top Half

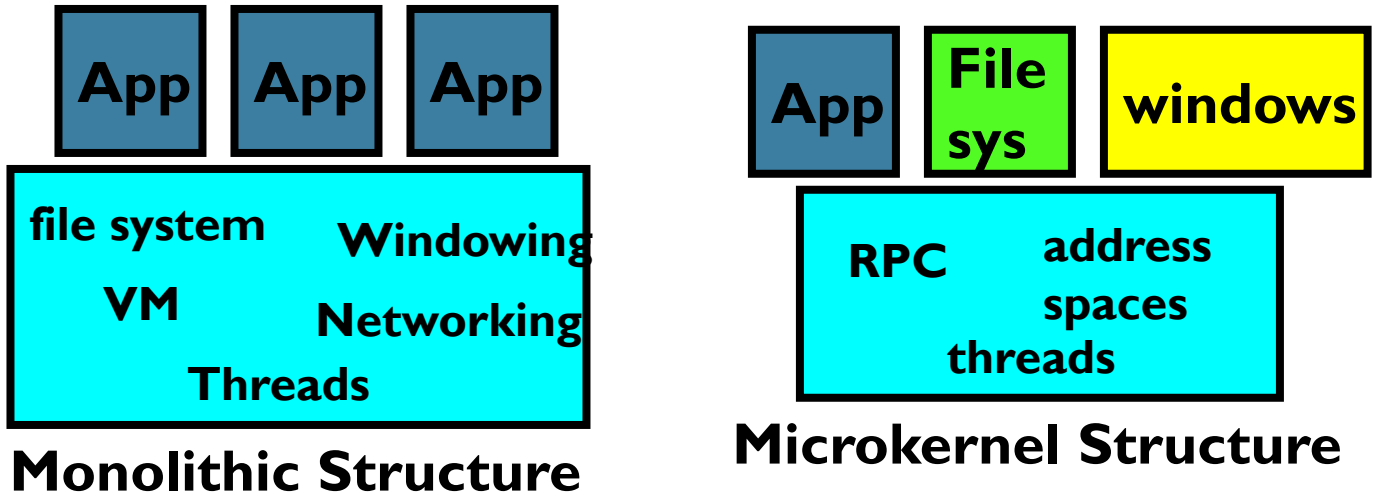
Device Driver Bottom Half

Device Hardware



Recall: Microkernels

- Split OS into **separate processes**
  - Example: File System, Network Driver are processes outside of the kernel
- Pass messages among these components (e.g., via RPC) instead of system calls

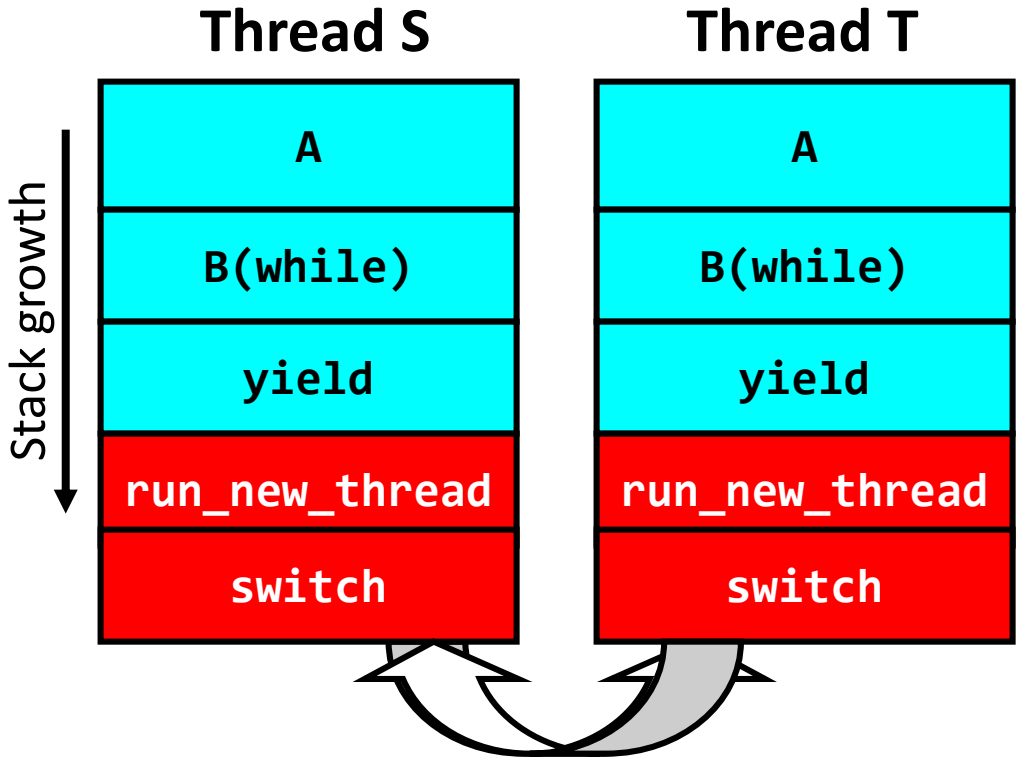


Recall: Switching Threads

- Consider the following code blocks:

```
func A() {
   B();
}
func B() {
   while(TRUE) {
      yield();
   }
}
```

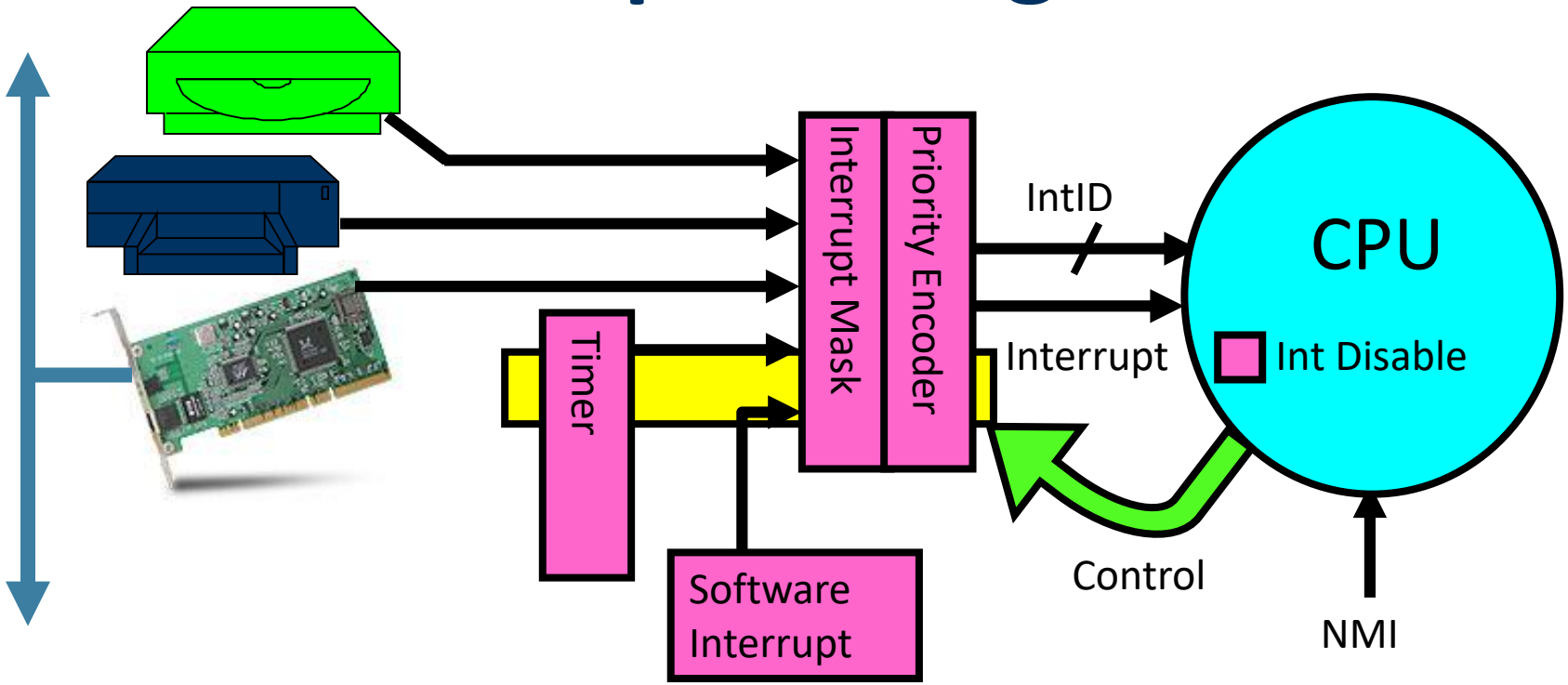
- Two threads, S and T, each run A



Thread S's `switch` returns to Thread T's (and vice versa)

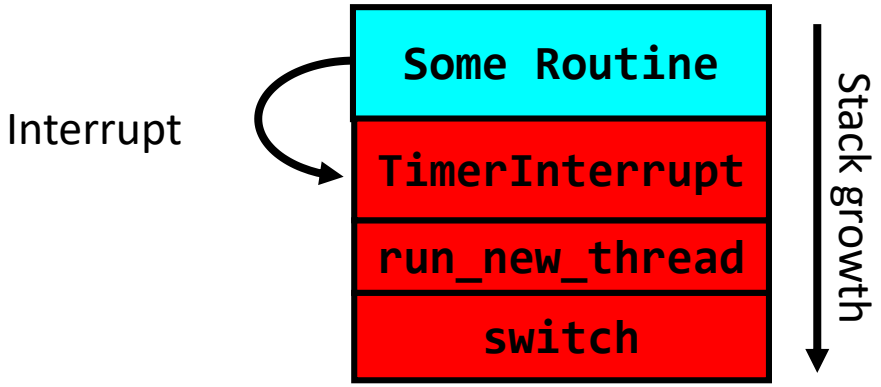
Pintos: switch.S

Recall: Interrupt Management



- Interrupt controller chooses interrupt request to honor
  - Interrupt identity specified with ID line
  - Software Interrupt Set/Cleared by Software
- CPU can disable all interrupts with internal flag
- Non-Maskable Interrupt line (NMI) can't be disabled

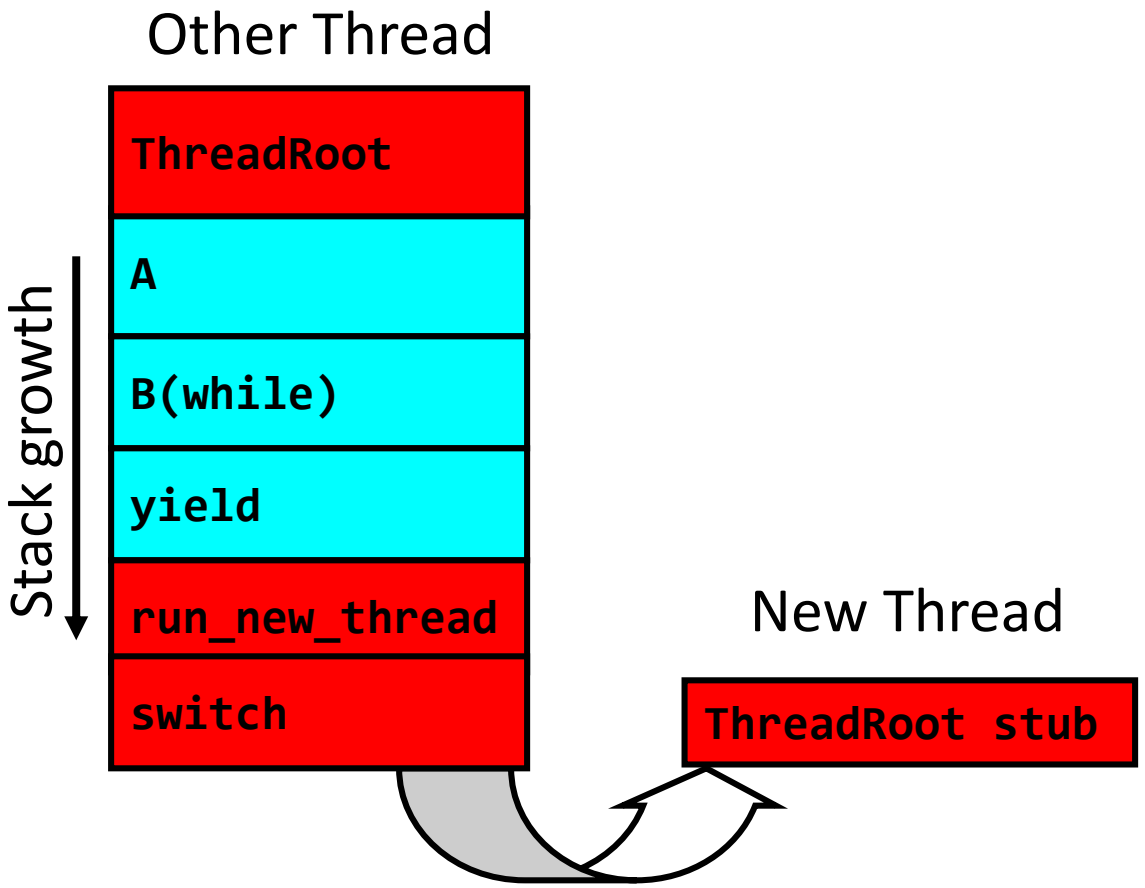
Recall: Preempting a Thread



- Timer Interrupt routine:

```
TimerInterrupt() {
    DoPeriodicHouseKeeping();
    run_new_thread();
}
```

Creating a New Thread



- Let `ThreadRoot` be the routine that the thread should start out running
- We need to set up the thread state so that, another thread can "return" into the beginning of `ThreadRoot`
  - This really starts the new thread

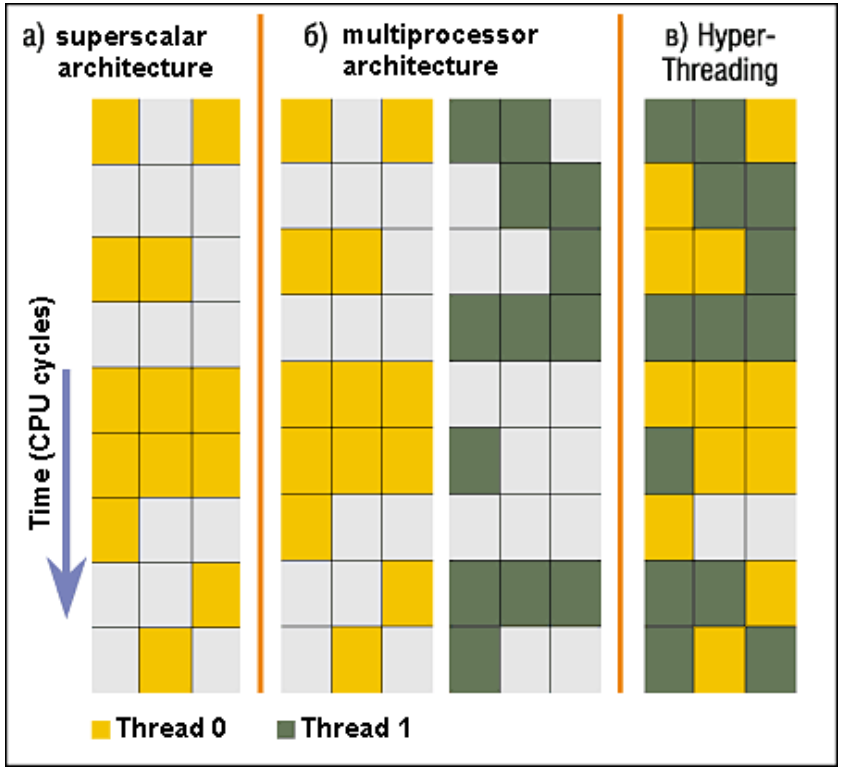
Bootstrapping Threads

```
ThreadRoot() {
  DoStartupHousekeeping();
  UserModeSwitch(); /* enter user mode */
  call fcnPtr(fcnArgPtr);
  ThreadFinish();
}
```

- Stack will grow and shrink with execution of thread
- **`ThreadRoot()`** never returns
  - **`ThreadFinish()`** destroys thread, invokes scheduler

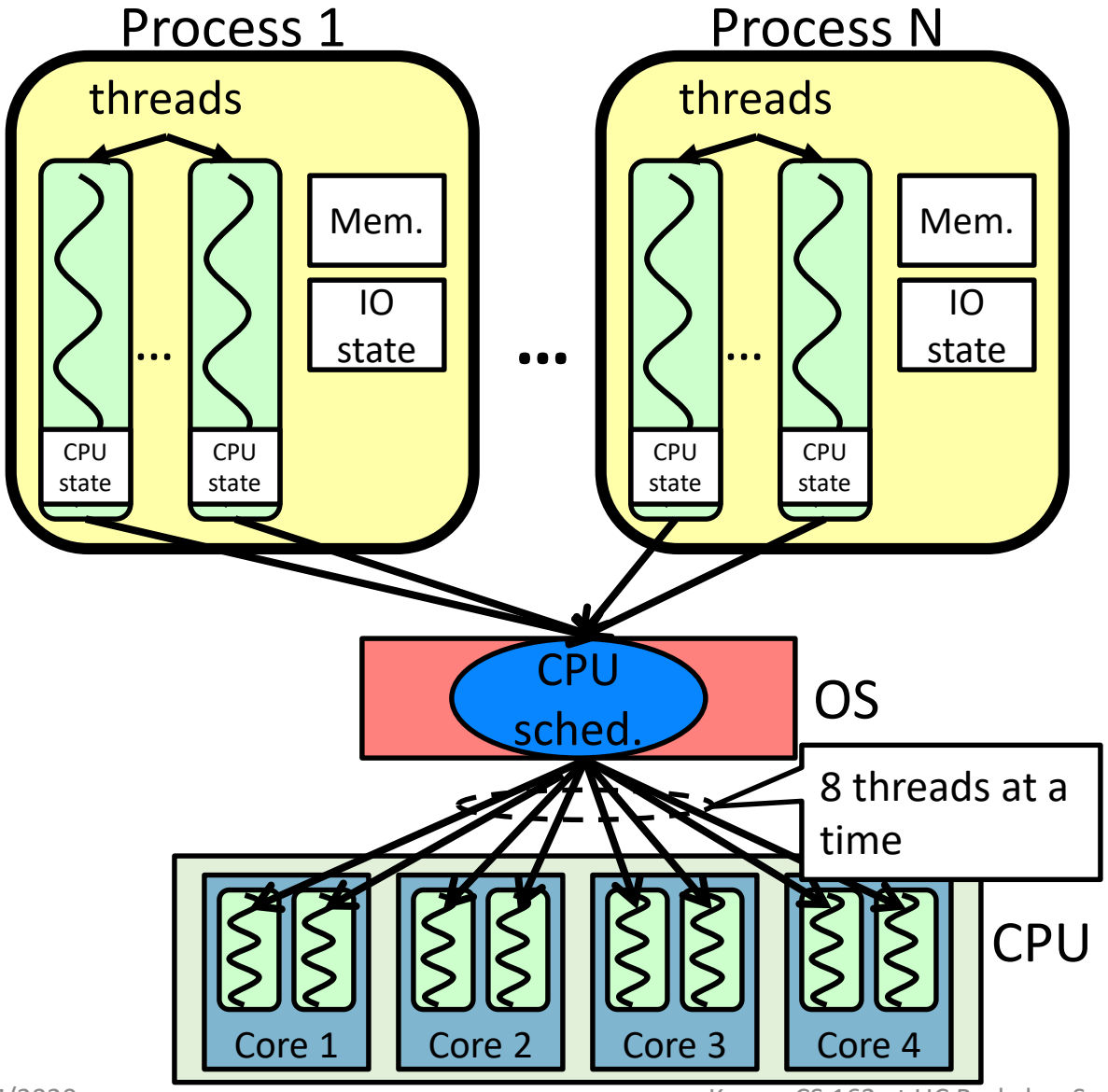
Aside: SMT/Hyperthreading

- Hardware technique
  - Superscalar processors try to execute multiple independent instructions in parallel
  - Hyperthreading allows a single core to process multiple instructions streams at once
  - But, speedup is sub-linear
- Originally called “Simultaneous Multithreading”
  - http://www.cs.washington.edu/research/smt/index.html
  - Intel, SPARC, Power (IBM)
- **From the OS perspective, this just looks like multiple cores**



Colored blocks show Instructions executed

Aside: SMT/Hyperthreading



- Switch overhead:
  - Same process: **low**
  - Different proc.: **high**
- Protection
  - Same proc: **low**
  - Different proc: **high**
- Sharing overhead
  - Same proc: **low**
  - Different proc: **high**

Recall: Race Conditions

- What are the possible values of x below?
- Initially `x == 0` and `y == 0`

Thread A	Thread B
`x = y + 1;`	`y = 2;`
	`y = y * 2;`

- 1 or 3 or 5 (non-deterministic)
- Race Condition: Thread A races against Thread B

Recall: Locks

- Locks provide two **atomic** operations:
  - Lock.acquire() – wait until lock is free; then mark it as busy
    - After this returns, we say the calling thread *holds* the lock
  - Lock.release() – mark lock as free
    - Should only be called by a thread that currently holds the lock
    - After this returns, the calling thread no longer holds the lock

- Provides *mutual exclusion* between two or more threads

Mutual Exclusion between Thread and Interrupt Handler

- Interrupt handler runs to completion
- Can’t acquire a lock in an interrupt handler (why?)

- Solution: Disable interrupts and restore them afterwards

```
int state = intr_disable();
<code manipulating shared data>
intr_restore(state);
```

Is Mutual Exclusion Enough?

No…

Recall: Relevant Definitions

- Synchronization: Coordination among threads, usually regarding shared data
- Mutual Exclusion: Ensuring only one thread does a particular thing at a time (one thread *excludes* the others)
  - Type of synchronization
- Critical Section: Code exactly one thread can execute at once
  - Result of mutual exclusion
- Lock: An object only one thread can hold at a time
  - Provides mutual exclusion

The Producer-Consumer Problem

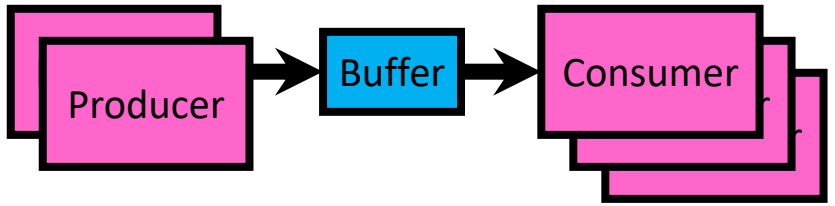
- Some processes/threads **produce** output that is **consumed** as input by other processes/threads

- Where have we seen this?
  - Pipes
  - Sockets

- GCC compiler – simple 1-1
  - `cpp | cc1 | cc2 | as | ld`

Producer-Consumer with a Bounded Buffer

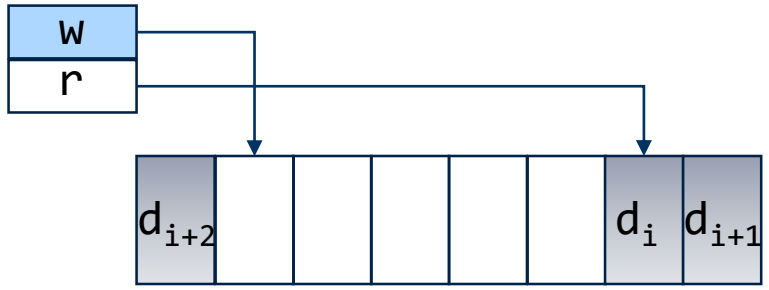
- Problem Definition
  - Producers puts things into a shared buffer
  - Consumers takes them out



- Don’t want producers and consumers to have to work in lockstep, so put a buffer (bounded) between them
  - Need synchronization to maintain integrity of the data structure and coordinate producers/consumers
  - Producer needs to wait if buffer is full
  - Consumer needs to wait if buffer is empty

Circular Buffer Data Structure (Sequential Case)

```
typedef struct buf {
  int write_index;
  int read_index;
  <type> *entries[BUFSIZE];
} buf_t;
```



- Insert: write & bump write ptr (enqueue)
- Remove: read & bump read ptr (dequeue)
- *How to tell if Full (on insert)?*
- *How to tell if Empty (on remove)?*
- *And what do you do if it is?*
- *What needs to be atomic?*

Producer-Consumer: Correctness

- Mutual exclusion:
  - Only one thread manipulates the buffer data structure at a time

- Synchronization requirements other than mutual exclusion:
  - If buffer is empty, consumer waits for the producer
  - If buffer is full, producer waits for consumer

Circular Buffer: Attempt #1

```
mutex buf_lock = <initially unlocked>
Producer(item) {
  acquire(&buf_lock);
  while (buffer full) {} // Wait for a free slot
  enqueue(item);
  release(&buf_lock);
}

Consumer() {
  acquire(&buf_lock);
  while (buffer empty) {} // Wait for a used slot
  item = dequeue();
  release(&buf_lock);
  return item;
}
```

Will we ever come out of the wait loop?

Circular Buffer: Attempt #2

```
mutex buf_lock = <initially unlocked>
Producer(item) {
  acquire(&buf_lock);
  while (buffer full) { release(&buf_lock); acquire(&buf_lock); }
  enqueue(item);
  release(&buf_lock);
}

Consumer() {
  acquire(&buf_lock);
  while (buffer empty) { release(&buf_lock); acquire(&buf_lock); }
  item = dequeue();
  release(&buf_lock);
  return item;
}
```

What happens when one is waiting for the other?

Recall: Semaphore

- Semaphores are a kind of generalized lock
  - First defined by Dijkstra in late 60s
  - Main synchronization primitive used in original UNIX (& Pintos)
- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
  - P() or down(): atomic operation that waits for semaphore to become positive, then decrements it by 1
  - V() or up(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any

P() stands for "*proberen*" (to test) and V() stands for "*verhogen*" (to increment) in Dutch

Recall: Two Important Semaphore Patterns

- **Mutual Exclusion:** (Like lock)
  - Called a "binary semaphore"

```
initial value of semaphore = 1;
semaphore.down();
// Critical section goes here
semaphore.up();
```

- **Signaling** other threads, e.g. **`ThreadJoin`**

```
Initial value of semaphore = 0

ThreadJoin {
   semaphore.down();
}
```

```
ThreadFinish {
    semaphore.up();
}
```

Producer-Consumer Synchronization

- Mutual exclusion:
  - Only one thread manipulates the buffer data structure at a time
    - Lock mutex;
- Synchronization requirements other than mutual exclusion:
  - If buffer is empty, consumer waits for the producer
    - Semaphore usedSlots;
  - If buffer is full, producer waits for consumer
    - Semaphore freeSlots;
- Rule of thumb: use a separate semaphore for each constraint

Producer-Consumer Code

```
Semaphore usedSlots = 0; // No slots used
Semaphore freeSlots = bufSize; // All slots free
Lock mutex = <initially unlocked>; // Nobody in critical sec.

Producer(item) {
  freeSlots.P();
  mutex.acquire();
  Enqueue(item);
  mutex.release();
  usedSlots.V();
}

Consumer() {
  usedSlots.P();
  mutex.acquire();
  item = Dequeue();
  mutex.release();
  freeSlots.V();
  return item;
}
```

Discussion

- What if we wrote the following?

```
Producer(item) {
    mutex.acquire();
    freeSlots.P();
    Enqueue(item);
    mutex.release();
    usedSlots.V();
}
```

```
Consumer() {
    usedSlots.P();
    mutex.acquire();
    item = Dequeue();
    mutex.release();
    freeSlots.V();
    return item;
}
```

Deadlock… more on this later

Discussion

- What if we wrote the following?

```
Producer(item) {
    freeSlots.P();
    mutex.acquire();
    Enqueue(item);
    usedSlots.V();
    mutex.release();
}
```

```
Consumer() {
    usedSlots.P();
    mutex.acquire();
    item = Dequeue();
    mutex.release();
    freeSlots.V();
    return item;
}
```

Still correct!

Announcements

- Congrats on finishing Quiz 1!
- Project 1 design docs due tonight
- Homework 3 will be released soon

Problems with Semaphores

- More powerful (and primitive) than locks
- Argument: Clearer to have separate constructs for
  - Mutual Exclusion: One thread can do something at a time
  - Waiting for a condition to become true
- Need to make sure a thread calls P() for every V()
  - Other tools are more flexible than this

Two Distinct Uses of Semaphores

"During system conception it transpired that we used the semaphores in two completely different ways. The difference is so marked that, looking back, one wonders whether it was really fair to present the two ways as uses of the very same primitives. On the one hand, we have the semaphores used for mutual exclusion, on the other hand, the private semaphores."

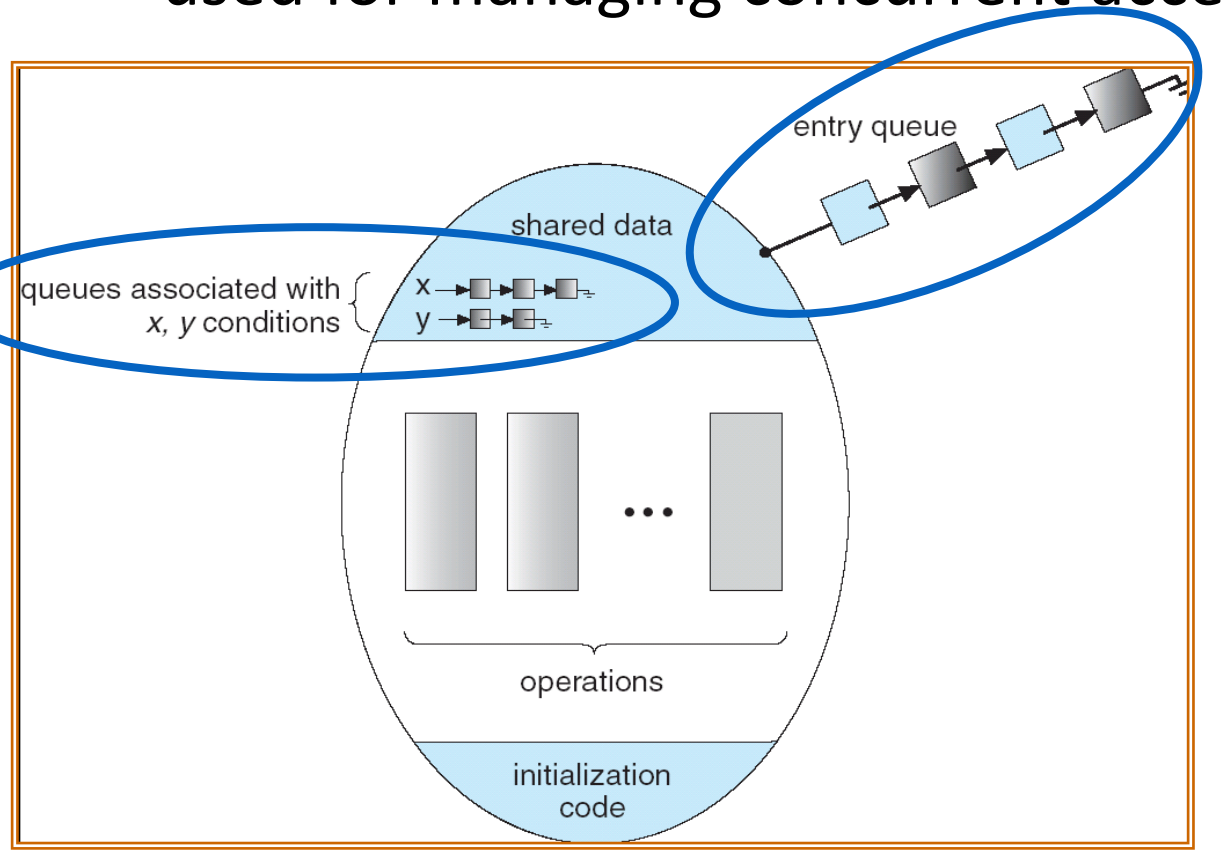
— Dijkstra, *The Structure of the "THE" Multiprogramming System*, 1968

Condition Variables

- **Queue of threads waiting *inside* a critical section**
  - **Typically, waiting until a condition on some variables becomes true**
  - **Variables typically are protected by a mutex**
- Operations:
  - **`wait(&lock)`:** Atomically release lock and go to sleep until condition variable is signaled. Re-acquire the lock before returning.
  - **`signal()`:** Wake up one waiting thread (if there is one)
  - **`broadcast()`:** Wake up all waiting threads
- **Rule:** Hold lock when using a condition variable

Monitors

- A monitor consists of a lock and zero or more condition variables used for managing concurrent access to shared data



- Lock: the lock provides mutual exclusion to shared data
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: make it possible to go to sleep inside critical section by atomically releasing lock at time we go to sleep

Producer-Consumer with Condition Variables

```
mutex buf_lock = <initially unlocked>
condvar no_longer_empty = <initially empty>
condvar no_longer_full = <initially empty>
Producer(item) {
  acquire(&buf_lock);
  while (buffer full) { cond_wait(&no_longer_full, &buf_lock); }
  enqueue(item);
  cond_signal(&no_longer_empty);
  release(&buf_lock);
}
Consumer() {
  acquire(&buf_lock);
  while (buffer empty) { cond_wait(&no_longer_empty, &buf_lock); }
  item = dequeue();
  cond_signal(&no_longer_full);
  release(&buf_lock);
  return item;
}
```

Why the `while` Loop?

- When a thread is woken up by `signal()`, it is simply marked as eligible to run

- It may or may not reacquire the lock immediately!
  - Another thread could be scheduled and "sneak in" make the condition it's waiting for no longer true
  - Need a loop to re-check condition on wakeup

- This is called Mesa Scheduling (Mesa-style Monitors)
- Most operating systems use Mesa-style Monitors!

Why the `while` Loop? (Example)

Thread A (Consumer)

```
acquire(&buf_lock);
while (buffer empty) {
  cond_wait(&not_empty, &buf_lock);

  // while loop checks condition
  // again, goes back to sleep
}
```

Thread B (Producer)

```
acquire(&buf_lock)
enqueue(item)
cond_signal(&not_empty);
release(&buf_lock);
```

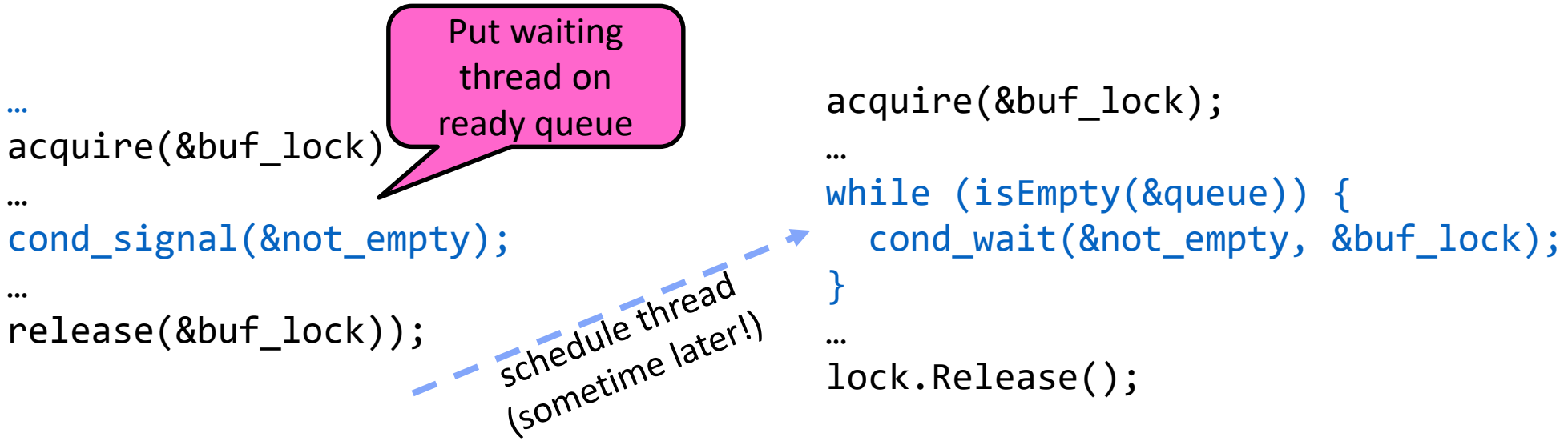
Thread C (Consumer)

```
acquire(&buf_lock);
~~while (buffer empty)~~
dequeue();
release(&buf_lock);
```

This is why the `while` loop is necessary!

Mesa Monitors

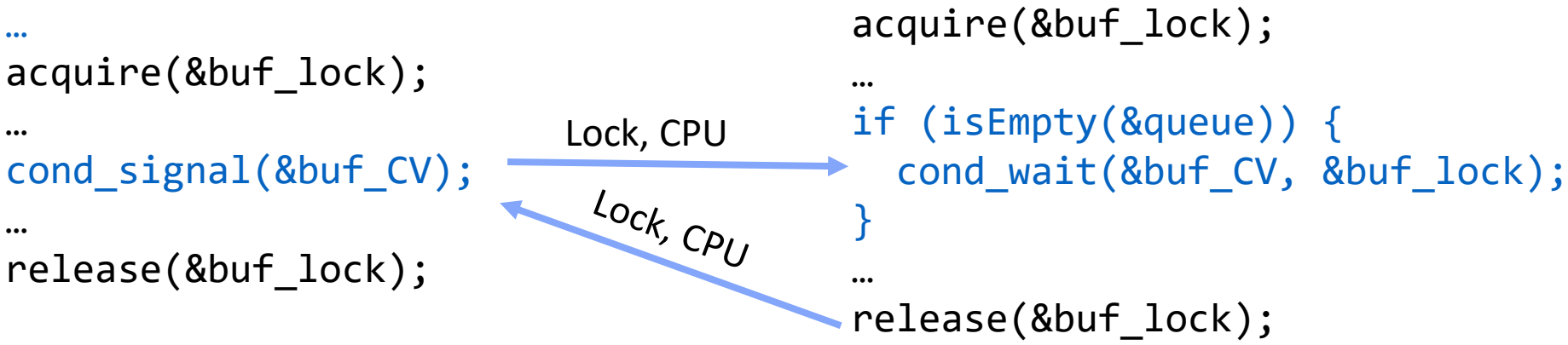
- Signaler keeps lock and CPU
- Waiter placed on ready queue with no special priority



- Practically, need to check condition again after wait
  - By the time the waiter gets scheduled, condition may be false again – so, just check again with the "while" loop
- Most real operating systems do this!
  - Efficient, easy to implement

Alternative: Hoare Monitors

- Named after British logician Tony Hoare
- When a thread call `signal()`:
  - It releases the lock and the OS context-switches to the waiter, which acquires the lock immediately
  - When waiter releases lock, the OS switches back to signaler



- Academically interesting, but not necessary!
  - Introduces complexity into the scheduler
  - Adds additional context switches

Mesa Monitors vs. Hoare Monitors

Mesa Monitor

```
while (buffer empty) {
  cond_wait(&not_empty, &buf_lock);
}
```

Hoare Monitor

```
if (buffer empty) {
  cond_wait(&not_empty, &buf_lock);
}
```

- In practice, almost all OSes implement Mesa monitors

Summary: Monitors

- Monitors represent the logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Basic structure of monitor-based program:

```
lock
while (need to wait) {
   condvar.wait();
}
unlock

do something so no need to wait

lock
condvar.signal();

unlock
```

Check and/or update state variables
Wait if necessary

Check and/or update state variables

Break

Programming Language Support for Concurrency and Synchronization

- Synchronization operations
- Exceptional conditions

Concurrency and Synchronization in C

- Standard approach: use **`pthreads`**, protect access to shared data structures
- One pitfall: consistently unlocking a mutex

```
int Rtn() {
  lock.acquire();
  …
  if (error) {
    lock.release();
    return errCode;
  }
  …
  lock.release();
  return OK;
}
```

Concurrency and Synchronization in C

- Harder with more locks

```
void Rtn() {
  lock1.acquire();
  …
  if (error) {
    lock1.release();
    return;
  }
  …
  lock2.acquire();
  …
  if (error) {
    lock2.release()
    lock1.release();
    return;
  }
  …
  lock2.release();
  lock1.release();
}
```

- Is goto a solution???

```
void Rtn() {
  lock1.acquire();
  …
  if (error) {
    goto release_lock1_and_return;
  }
  …
  lock2.acquire();
  …
  if (error) {
    goto release_both_and_return;
  }
  …
release_both_and_return:
  lock2.release();
release_lock1_and_return:
  lock1.release();
}
```

C++ Lock Guards

```
#include <mutex>
int global_i = 0;
std::mutex global_mutex;

void safe_increment() {
  std::lock_guard<std::mutex> lock(global_mutex);
  …
  global_i++;
  // Mutex released when ‘lock’ goes out of scope
}
```

Python `with` Keyword

- More versatile than we'll show here (can be used to close files, database connections, etc.)

```
lock = threading.Lock()
…
with lock: # Automatically calls acquire()
   some_var += 1
   …
# release() called however we leave block
```

Java synchronized Keyword

- Every Java object has an associated lock:
  - Lock is acquired on entry and released on exit from a synchronized method
  - Lock is properly released if exception occurs inside a synchronized method
  - Mutex execution of synchronized methods (beware deadlock)

```
class Account {
   private int balance;

   // object constructor
   public Account (int initialBalance) {
      balance = initialBalance;
   }
   public synchronized int getBalance() {
      return balance;
   }
   public synchronized void deposit(int amount) {
      balance += amount;
   }
}
```

Java Support for Monitors

- Along with a lock, every object has a **single** condition variable associated with it

- To wait inside a synchronized method:
  - **`void wait();`**
  - **`void wait(long timeout);`**

- To signal while in a synchronized method:
  - **`void notify();`**
  - **`void notifyAll();`**

Go Language Support for Concurrency

- Go was designed with concurrent applications in mind

- Some language aspects we'll talk about today:
  - `defer` keyword
  - Channels

- Some language aspects we won't talk about today (but may revisit):
  - Goroutines
  - `select` keyword
  - Contexts

Go defer Keyword

```
func Rtn() {
  lock.Lock()
  …
  if error {
    lock.Unlock()
    return
  }
  …
  lock.Unlock()
  return
}
```

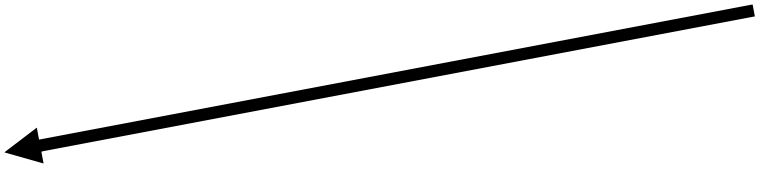
- Solution: use defer

```
func Rtn() {
  lock.Lock()
  defer lock.Unlock()
  …
  if error {
    return
  }
  …
  return
}
```

Go defer Keyword

- The queue of "deferred" calls is maintained dynamically

```
func Rtn() {
  lock1.Lock()
  defer lock1.Lock()
  …
  if condition {
    lock2.Lock()
    defer lock2.Unlock()
  }
  …
  return
}
```



- lock1 is always unlocked here
- lock2 is unlocked here only if the condition was true earlier

Go Channels

- A channel is a bounded buffer *in userspace*
  - Writes block if buffer is full
  - Reads block if buffer is empty

- "Do not communicate by sharing memory; instead, share memory by communicating."
  - From *Effective Go*

- Channels are the preferred mechanism for synchronization
  - Mutexes and condition variables are still supported, as in pthreads

Go Channels

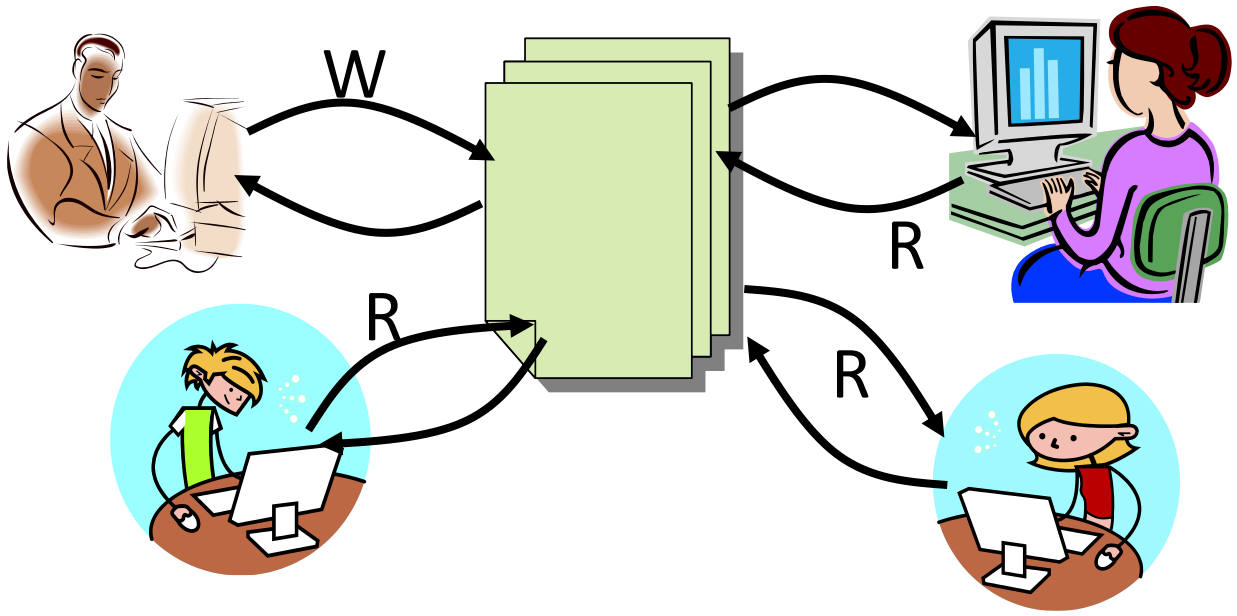
- Semantics similar to pipes, with the following differences:
  - Used within a single process (not across processes)
  - Carries language objects/structs, not bytes (no marshalling/unmarshalling)

```
var x chan int = make(chan int, 5)
x <- 162
y := <- x
fmt.Println(y) // Prints 162
```

Conclusion

- We studied synchronization primitives to wait until an event
  - Mutual exclusion isn't enough!
- Monitors: A lock plus one or more condition variables
  - Always acquire lock before accessing shared data
  - Use condition variables to wait inside critical section
    - Three Operations: `Wait()`, `Signal()`, and `Broadcast()`
    - Some languages support monitors directly
- Monitors represent the logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed

Readers-Writers Problem



- Consider a shared database
- Two classes of users:
  - Readers – never modify DB
  - Writers – read and modify DB
- Is using a single lock on the whole DB sufficient?
  - Yes, but not ideal
  - Want to allow multiple concurrent readers

Reader-Writer Correctness

- Readers can access when no writers
- Writers can access when no readers **and no other writers**

- A lock will satisfy these requirements
  - But we want to allow **multiple readers**
  - Better efficiency

Reader-Writer with Monitors

```
Reader() {
  Wait until no active writers
  Access database
  Maybe wake up a writer
}
Writer() {
  Wait until no active readers or
writers
  Access database
  Maybe wakeup reader or writer
}
```

- Lock (for mutual exclusion)
- int activeReaders
- condvar okToRead
- int activeWriters
- condvar okToWrite

Reader Version 1

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0) { // Is it safe to read?
       okToRead.wait(&lock); // Sleep on cond var
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
 }
```

- AR = "Active Readers"
- AW = "Active Writers"

Writer Version 1

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
       okToWrite.wait(&lock); // Sleep on cond var
    }
    AW++;  // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;    // No longer active
    okToWrite.signal(); // Wake up one writer
    okToRead.broadcast(); // Wake up all readers
    lock.Release();
 }
```

- AR = "Active Readers"
- AW = "Active Writers"

Writer Version 1: Starvation

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
       okToWrite.wait(&lock); // Sleep on cond var
    }
    AW++;  // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;    // No longer active
    okToWrite.signal(); // Wake up one writer
    okToRead.broadcast(); // Wake up all readers
    lock.Release();
 }
```

If there are always readers, this is always true! Writer starves

Writer Version 1: Conflict

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
       okToWrite.wait(&lock); // Sleep on cond var
    }
    AW++;  // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;    // No longer active
    okToWrite.signal(); // Wake up one writer
    okToRead.broadcast(); // Wake up all readers
    lock.Release();
 }
```

If a writer gets the lock, all the readers wake up anyway, re-check the condition, and go to sleep

Reader-Writer with Monitors, Version 2

```
Reader() {
  Wait until no active or waiting writers
  Access database
  Maybe wake up a writer
}
Writer() {
  Wait until no active readers or writers
  Access database
  If waiting writer, wake it up
  Otherwise, wakeup readers
}
```

Reader Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- AR = “Active Readers”
- AW = “Active Writers”
- WR = “Waiting Readers”
- WW = “Waiting Writers”

Writer Version 2

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
        WW++;
        okToWrite.wait(&lock); // Sleep on cond var
        WW--;
    }
    AW++;   // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;     // No longer active
    if (WW > 0)
        okToWrite.signal(); // Wake up one writer
    else
        okToRead.broadcast(); // Wake up all readers
    lock.Release();
}
```

- AR = “Active Readers”
- AW = “Active Writers”
- WR = “Waiting Readers”
- WW = “Waiting Writers”

Reader-Writer Design Choices

- Reader starvation:

```
while (AW > 0 || WW > 0) { // Safe to read?
  okToRead.wait(&lock); // Sleep on cond var
}
```

- "Writer-biased" Lock
  - Can favor readers by changing conditions on wait loops
  - Other possibilities, e.g. track readers waiting since before current writer started

Fair Solution to the Reader-Writer Problem?

- Ideas?

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR++;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 0, WR = 0, AW = 0, WW = 0
- R1 comes along (nobody waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) {  // Is it safe to read?
        WR++;
        okToRead.wait(&lock); // Sleep on cond var
        WR++;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
        okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 0, WR = 0, AW = 0, WW = 0
- R1 comes along (nobody waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR++;
    }
    AR++; // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;   // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 1, WR = 0, AW = 0, WW = 0

- R1 comes along (nobody waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR++;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 1, WR = 0, AW = 0, WW = 0
- R1 comes along (nobody waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR++;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 1, WR = 0, AW = 0, WW = 0
- R1 accessing DB

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR++;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 1, WR = 0, AW = 0, WW = 0
- R2 comes along (R1 accessing DB)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) {  // Is it safe to read?
        WR++;
        okToRead.wait(&lock); // Sleep on cond var
        WR++;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
        okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 1, WR = 0, AW = 0, WW = 0
- R2 comes along (R1 accessing DB)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR++;
    }
    AR++; // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 2, WR = 0, AW = 0, WW = 0

- R2 comes along (R1 accessing DB)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR++;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 2, WR = 0, AW = 0, WW = 0

- R2 comes along (R1 accessing DB)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR++;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 2, WR = 0, AW = 0, WW = 0
- R1 & R2 accessing DB

Simulation of Reader-Writer, Version 2

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
        WW++;
        okToWrite.wait(&lock); // Sleep on cond var
        WW--;
    }
    AW++;   // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;     // No longer active
    if (WW > 0)
        okToWrite.signal(); // Wake up one writer
    else
        okToRead.broadcast(); // Wake up all readers
    lock.Release();
}
```

- Sequence of arrivals:
  R1, R2, **W1**, R3
- AR = 2, WR = 0,
  AW = 0, WW = 0

- W1 comes along
  (R1 & R2 accessing DB)

Simulation of Reader-Writer, Version 2

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
        WW++;
        okToWrite.wait(&lock); // Sleep on cond var
        WW--;
    }
    AW++;   // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;     // No longer active
    if (WW > 0)
        okToWrite.signal(); // Wake up one writer
    else
        okToRead.broadcast(); // Wake up all readers
    lock.Release();
}
```

- Sequence of arrivals: R1, R2, **W1**, R3
- AR = 2, WR = 0, AW = 0, WW = 0

- W1 comes along (R1 & R2 accessing DB)

Simulation of Reader-Writer, Version 2

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
        WW++;
        okToWrite.wait(&lock); // Sleep on cond var
        WW--;
    }
    AW++;   // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;     // No longer active
    if (WW > 0)
        okToWrite.signal(); // Wake up one writer
    else
        okToRead.broadcast(); // Wake up all readers
    lock.Release();
}
```

- Sequence of arrivals: R1, R2, **W1**, R3
- AR = 2, WR = 0, AW = 0, WW = 1

- W1 comes along (R1 & R2 accessing DB)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, R2, W1, **R3**
- AR = 2, WR = 0, AW = 0, WW = 1

- R3 comes along (R1 & R2 accessing DB, W1 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) {  // Is it safe to read?
        WR++;
        okToRead.wait(&lock); // Sleep on cond var
        WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
        okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, R2, W1, **R3**
- AR = 2, WR = 0, AW = 0, WW = 1

- R3 comes along (R1 & R2 accessing DB, W1 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, R2, W1, **R3**
- AR = 2, WR = 1, AW = 0, WW = 1

- R1 & R2 accessing DB, W1 & R3 waiting

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 2, WR = 1, AW = 0, WW = 1

- R2 finishes (R1 accessing DB, W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;   // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 1, WR = 1, AW = 0, WW = 1

- R2 finishes (R1 accessing DB, W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 1, WR = 1, AW = 0, WW = 1

- R2 finishes (R1 accessing DB, W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: R1, **R2**, W1, R3
- AR = 1, WR = 1, AW = 0, WW = 1

- R2 finishes (R1 accessing DB, W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
 }
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 1, WR = 1, AW = 0, WW = 1
- R1 finishes (W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;   // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 0, WR = 1, AW = 0, WW = 1

- R1 finishes (W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 0, WR = 1, AW = 0, WW = 1
- R1 finishes (W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
 }
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 0, WR = 1, AW = 0, WW = 1
- R1 finishes (W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Reader() {
    // First check self into system
    lock.Acquire();
    while (AW > 0 || WW > 0) { // Is it safe to read?
       WR++;
       okToRead.wait(&lock); // Sleep on cond var
       WR--;
    }
    AR++;  // Now we are active!
    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
    AR--;    // No longer active
    if (AR == 0 && WW > 0)  // No other active readers
       okToWrite.signal();  // Wake up one writer
    lock.Release();
}
```

- Sequence of arrivals: **R1**, R2, W1, R3
- AR = 0, WR = 1, AW = 0, WW = 1
- R1 finishes (W1 & R3 waiting)

Simulation of Reader-Writer, Version 2

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
        WW++;
        okToWrite.wait(&lock); // Sleep on cond var
        WW--;
    }
    AW++;   // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;     // No longer active
    if (WW > 0)
        okToWrite.signal(); // Wake up one writer
    else
        okToRead.broadcast(); // Wake up all readers
    lock.Release();
}
```

- Sequence of arrivals: R1, R2, **W1**, R3
- AR = 0, WR = 1, AW = 0, WW = 0

- W1 is awakened (R3 waiting)

Simulation of Reader-Writer, Version 2

```
Writer() {
    // First check self into system
    lock.Acquire();
    while (AR > 0 || AW > 0) { // Is it safe to write?
        WW++;
        okToWrite.wait(&lock); // Sleep on cond var
        WW--;
    }
    AW++;  // Now we are active!
    lock.release();
    // Perform actual read/write access
    AccessDatabase(ReadWrite);
    // Now, check out of system
    lock.Acquire();
    AW--;     // No longer active
    if (WW > 0)
        okToWrite.signal(); // Wake up one writer
    else
        okToRead.broadcast(); // Wake up all readers
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    lock.release();
    // Perform actual read-only access
    AccessDatabase(ReadOnly);
    // Now, check out of system
    lock.Acquire();
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