Concurrency and Synchronization

Motivation

- Operating systems (and application programs) often need to be able to handle multiple things happening at the same time
  - Process execution, interrupts, background tasks, system maintenance
- Humans are not very good at keeping track of multiple things happening simultaneously
- Threads and synchronization are an abstraction to help bridge this gap

Why Concurrency?

- Servers
  - Multiple connections handled simultaneously
- Parallel programs
  - To achieve better performance
- Programs with user interfaces
  - To achieve user responsiveness while doing computation
- Network and disk bound programs
  - To hide network/disk latency

Definitions

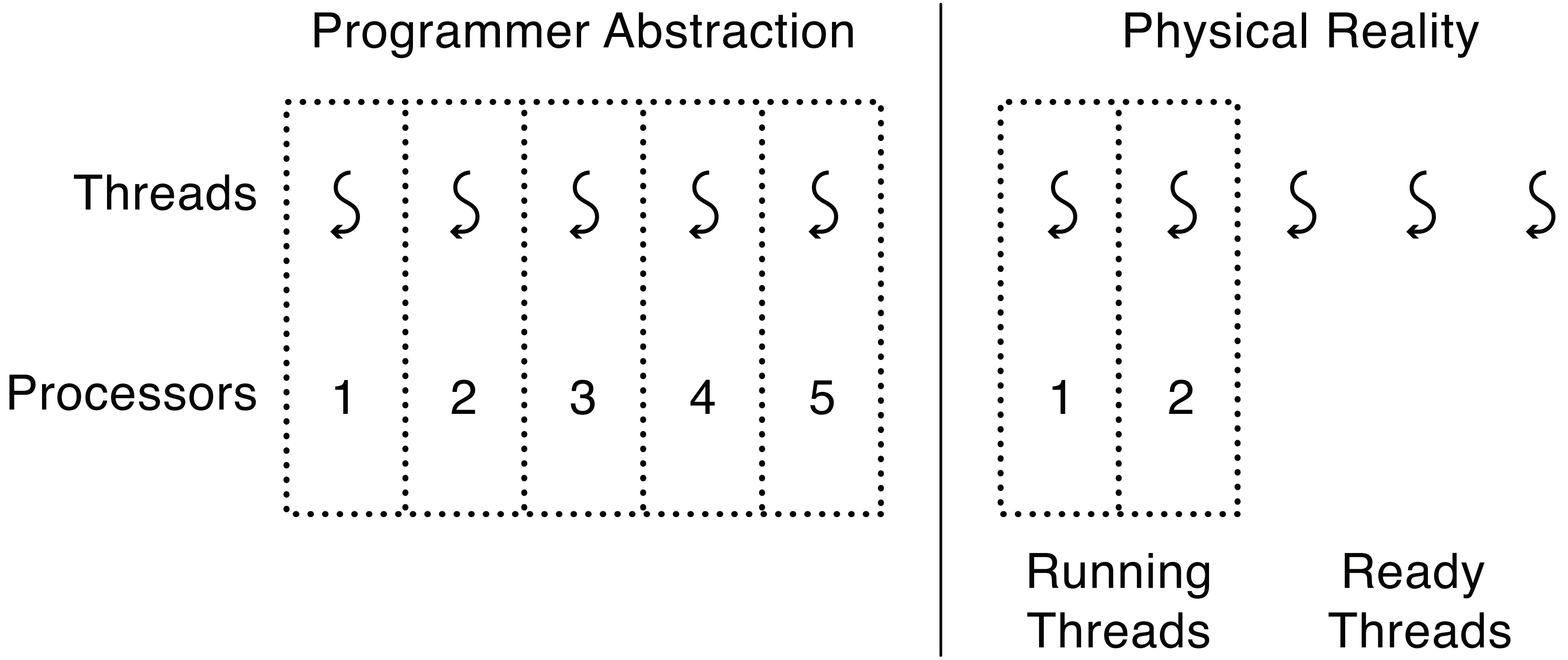
- A thread is a single execution sequence that represents a separately schedulable task
  - Single execution sequence: familiar programming model
  - Separately schedulable: OS can run or suspend a thread at any time
- Protection is an orthogonal concept
  - Can have one or many threads per protection domain

Threads in the Kernel and at User-Level

- Multi-process kernel
  - Multiple single-threaded processes
  - System calls access shared kernel data structures
- Multi-threaded kernel
  - multiple threads, sharing kernel data structures, capable of using privileged instructions
  - UNIX daemon processes -> multi-threaded kernel
- Multiple multi-threaded user processes
  - Each with multiple threads, sharing same data structures, isolated from other user processes
  - Plus a multi-threaded kernel

Thread Abstraction

- Infinite number of processors
- Threads execute with variable speed
  - Programs must be designed to work with any schedule



Question

Why do threads execute at variable speed?

Programmer vs. Processor View

Programmer's View

```
.
.
.
x = x + 1;
y = y + x;
z = x + 5y;
.
.
.
```

Possible Execution #1

```
.
.
.
x = x + 1;
y = y + x;
z = x + 5y;
.
.
.
```

Possible Execution #2

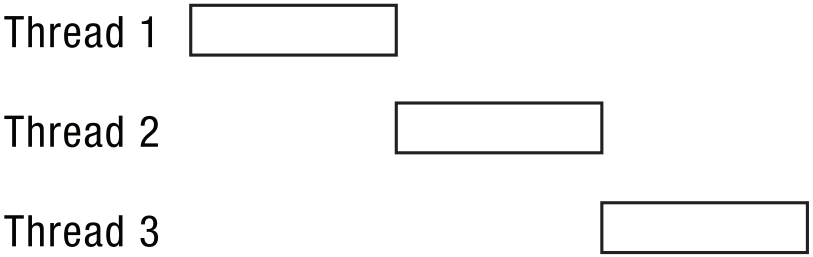
```
.
.
.
x = x + 1;
..............
Thread is suspended.
Other thread(s) run.
Thread is resumed.
...............
y = y + x;
z = x + 5y;
```

Possible Execution #3

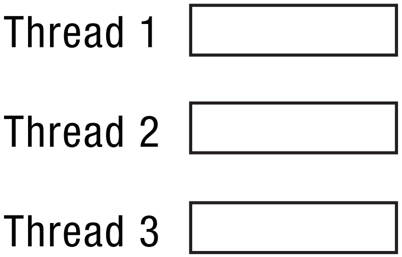
```
.
.
.
x = x + 1;
y = y + x;
...............
Thread is suspended.
Other thread(s) run.
Thread is resumed.
................
z = x + 5y;
```

Possible Executions

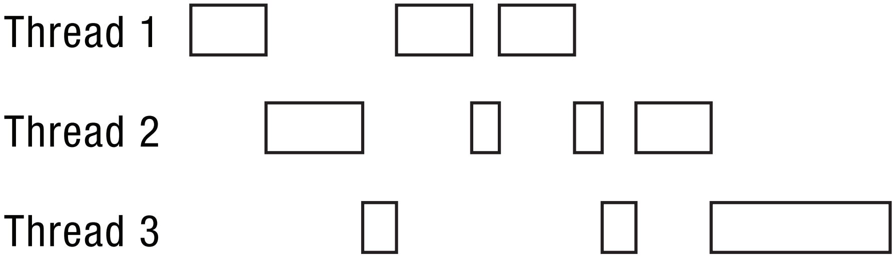
One Execution



Another Execution



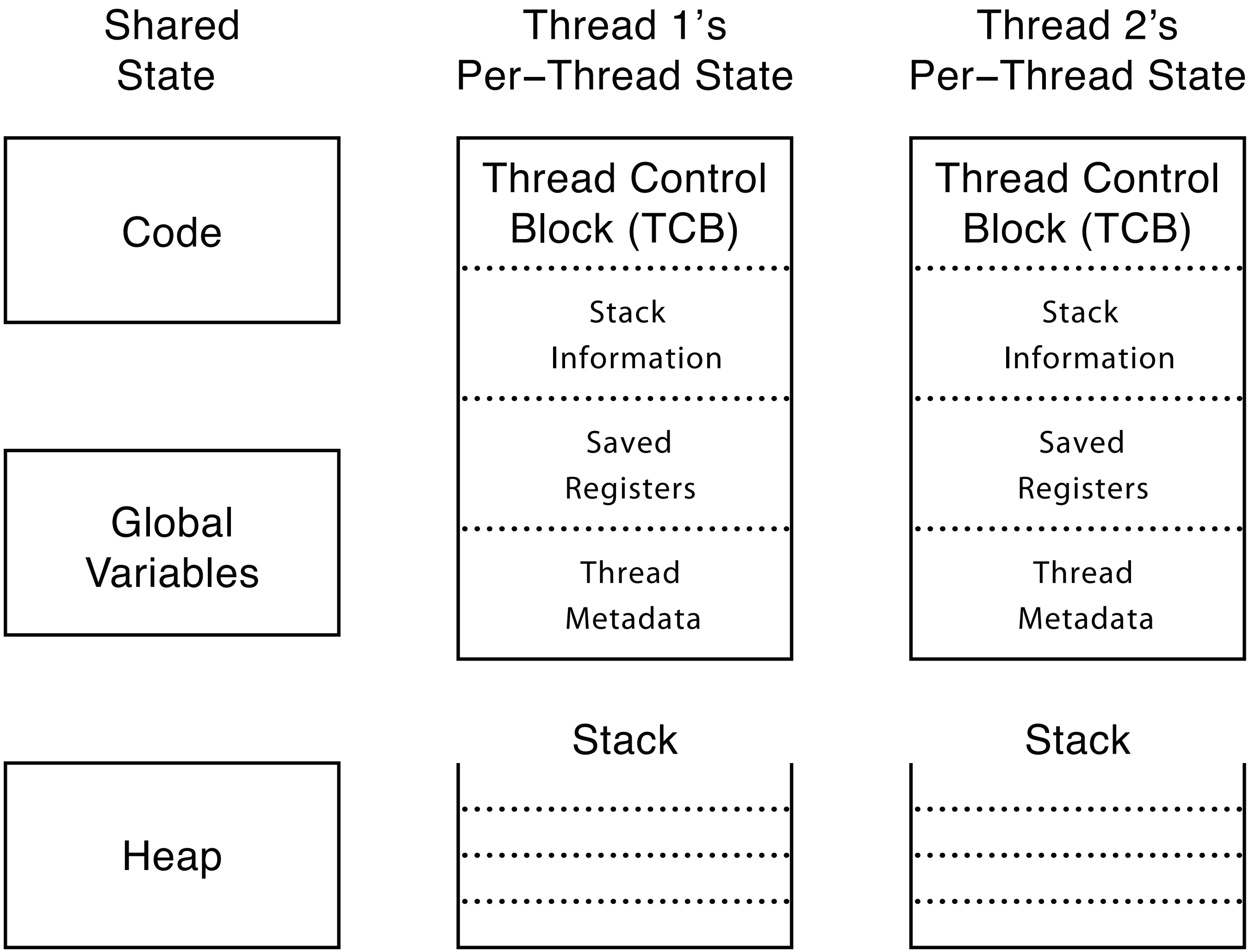
Another Execution



Thread Operations

- thread_create(thread, func, args)
  - Create a new thread to run func(args)
- thread_yield()
  - Relinquish processor voluntarily
- thread_join(thread)
  - In parent, wait for forked thread to exit, then return
- thread_exit
  - Quit thread and clean up, wake up joiner if any

Thread Data Structures



Shared State

Code

Global Variables

Heap

Thread 1's Per–Thread State

Thread Control Block (TCB)

Stack Information

Saved Registers

Thread Metadata

Stack

Thread 2's Per–Thread State

Thread Control Block (TCB)

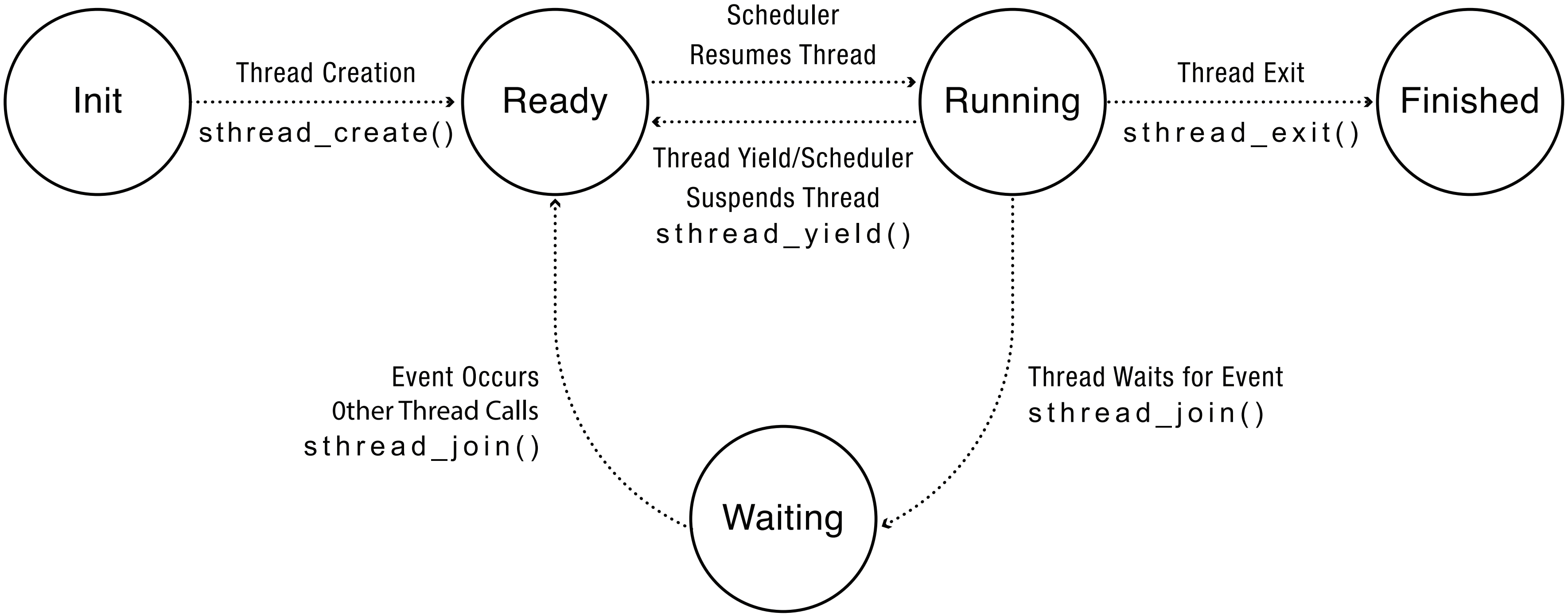
Stack Information

Saved Registers

Thread Metadata

Stack

Thread Lifecycle



Init

Thread Creation
sthread_create()

Ready

Scheduler
Resumes Thread

Running

Thread Exit
sthread_exit()

Finished

Thread Yield/Scheduler
Suspends Thread
sthread_yield()

Event Occurs
Other Thread Calls
sthread_join()

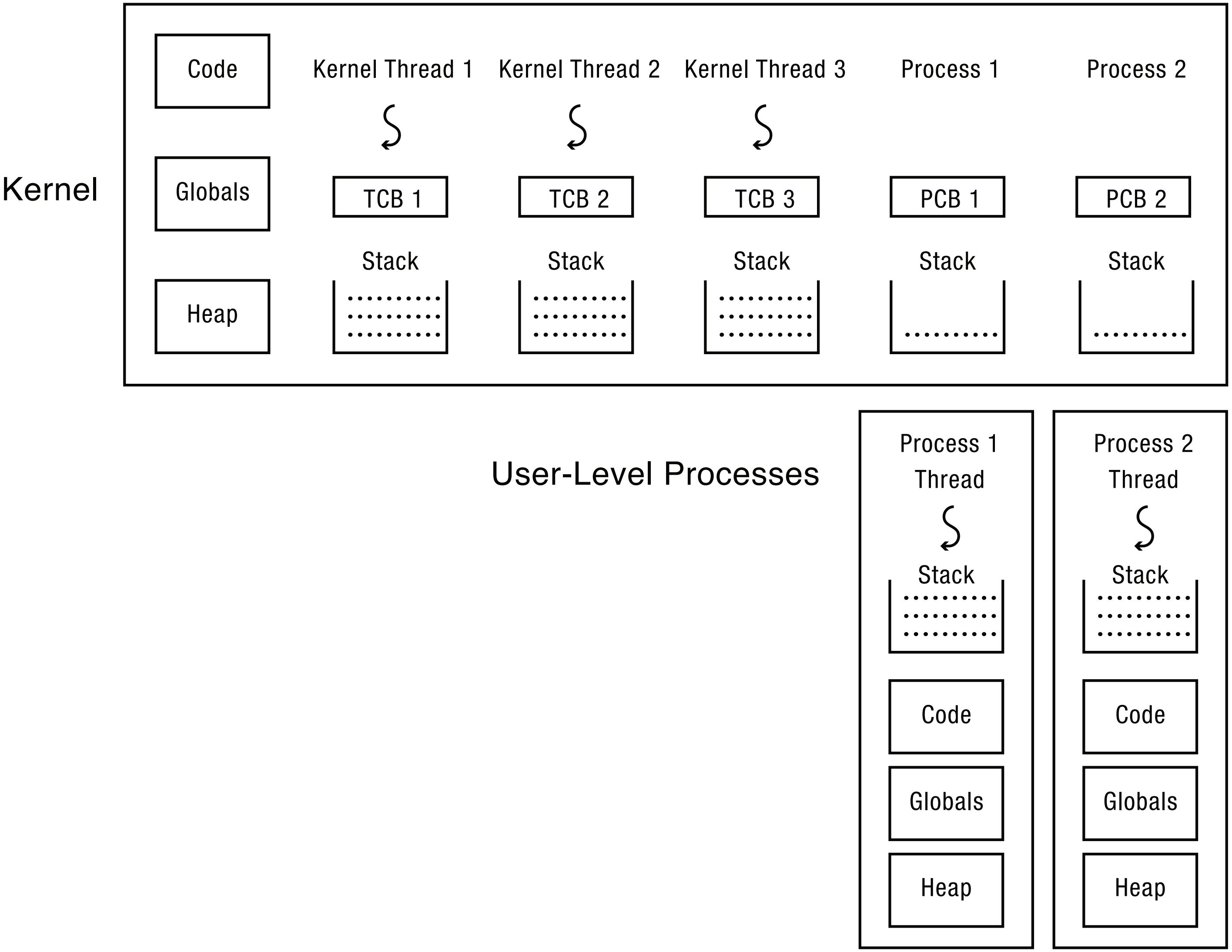
Thread Waits for Event
sthread_join()

Waiting

Implementing Threads: Roadmap

- Kernel threads
  - Thread abstraction only available to kernel
  - To the kernel, a kernel thread and a single threaded user process look quite similar
- Multithreaded processes using kernel threads (Linux, MacOS, Windows)
  - Kernel thread operations available via syscall
- User-level threads (Windows)
  - Thread operations without system calls

Multithreaded OS Kernel



Implementing threads

- Thread_fork(func, args)
  - Allocate thread control block
  - Allocate stack
  - Build stack frame for base of stack (stub)
  - Put func, args on stack
  - Put thread on ready list
  - Will run sometime later (maybe right away!)
- stub(func, args):
  - Call (*func)(args)
  - If return, call thread_exit()

Thread Stack

- What if a thread puts too many procedures on its stack?
  - What happens in Java?
  - What happens in the Linux kernel?
  - What happens in OS/161?
  - What *should* happen?

Thread Context Switch

- Voluntary
  - Thread_yield
  - Thread_join (if child is not done yet)
- Involuntary
  - Interrupt or exception
  - Some other thread is higher priority

Voluntary thread context switch

- Save registers on old stack
- Switch to new stack, new thread
- Restore registers from new stack
- Return
- Exactly the same with kernel threads or user threads
  - xv6 hint: thread switch between kernel threads, not between user process and kernel thread

OS/161 switchframe_switch

```
/* a0: pointer to old thread control block
 * a1: pointer to new thread control block */
/* Allocate stack space for 10 registers. */
 addi sp, sp, -40
 /* Save the registers */
 sw   ra, 36(sp)
 sw   gp, 32(sp)
 sw   s8, 28(sp)
 sw   s6, 24(sp)
 sw   s5, 20(sp)
 sw   s4, 16(sp)
 sw   s3, 12(sp)
 sw   s2, 8(sp)
 sw   s1, 4(sp)
 sw   s0, 0(sp)
 /* Store old stack pointer in old thread */
 sw   sp, 0(a0)
```

```
/* Get new stack pointer from new thread */
 lw   sp, 0(a1)
 nop        /* delay slot for load */
/* Now, restore the registers */
 lw   s0, 0(sp)
 lw   s1, 4(sp)
 lw   s2, 8(sp)
 lw   s3, 12(sp)
 lw   s4, 16(sp)
 lw   s5, 20(sp)
 lw   s6, 24(sp)
 lw   s8, 28(sp)
 lw   gp, 32(sp)
 lw   ra, 36(sp)
 nop              /* delay slot for load */
 j ra                     /* and return. */
 addi sp, sp, 40     /* in delay slot */
```

x86 switch_threads

```
# Save caller’s register state
#  NOTE: %eax, etc. are ephemeral
pushl %ebx
pushl %ebp
pushl %esi
pushl %edi

# Get offset of struct thread.stack
mov thread_stack_ofs, %edx
# Save current stack pointer
movl SWITCH_CUR(%esp), %eax
movl %esp, (%eax,%edx,1)
```

```
# Change stack pointer;
# stack points to new TCB
movl SWITCH_NEXT(%esp), %ecx
movl (%ecx,%edx,1), %esp

# Restore caller's register state.
popl %edi
popl %esi
popl %ebp
popl %ebx
ret
```

A Subtlety

- Thread_create puts new thread on ready list
- When it first runs, some thread calls switchframe
  - Saves old thread state to stack
  - Restores new thread state from stack
- Set up new thread's stack as if it had saved its state in switchframe
  - "returns" to stub at base of stack to run func

Two Threads Call Yield

Thread 1’s instructions	**Thread 2’s instructions**	**Processor’s instructions**
“return” from thread_switch into stub		“return” from thread_switch into stub
call go		call go
call thread_yield		call thread_yield
choose another thread		choose another thread
call thread_switch		call thread_switch
save thread 1 state to TCB		save thread 1 state to TCB
load thread 2 state		load thread 2 state
	“return” from thread_switch into stub	“return” from thread_switch into stub
	call go	call go
	call thread_yield	call thread_yield
	choose another thread	choose another thread
	call thread_switch	call thread_switch
	save thread 2 state to TCB	save thread 2 state to TCB
	load thread 1 state	load thread 1 state
return from thread_switch		return from thread_switch
return from thread_yield		return from thread_yield
call thread_yield		call thread_yield
choose another thread		choose another thread
call thread_switch		call thread_switch

Involuntary Thread/Process Switch

- Timer or I/O interrupt
  - Tells OS some other thread should run
- Simple version
  - End of interrupt handler calls switch()
  - When resumed, return from handler resumes kernel thread or user process
  - Thus, processor context is saved/restored twice (once by interrupt handler, once by thread switch)

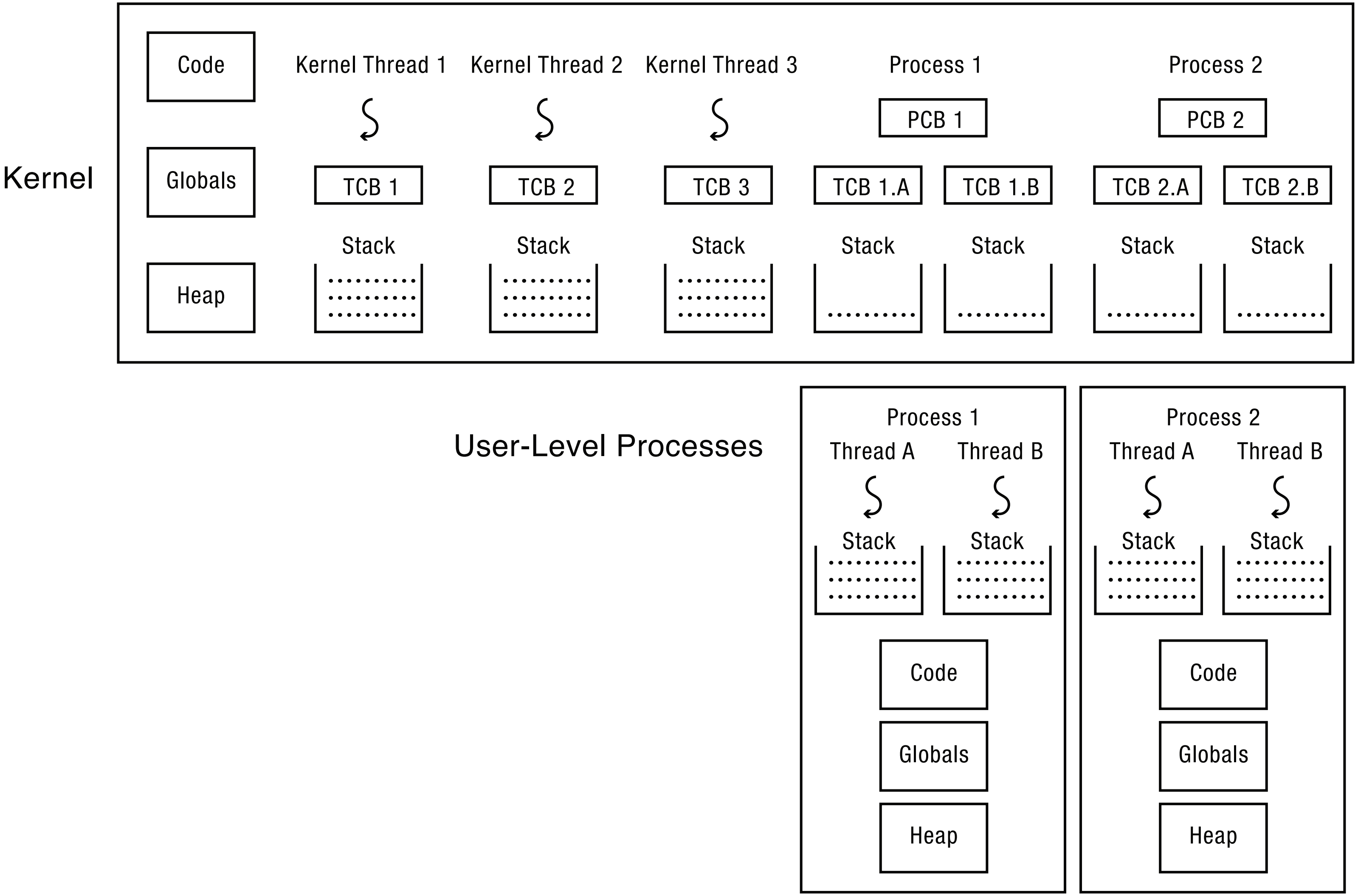
Faster Thread/Process Switch

- What happens on a timer (or other) interrupt?
  - Interrupt handler saves state of interrupted thread
  - Decides to run a new thread
  - Throw away current state of interrupt handler!
  - Instead, set saved stack pointer to trapframe
  - Restore state of new thread
  - On resume, pops trapframe to restore interrupted thread

Multithreaded User Processes (Take 1)

- User thread = kernel thread (Linux, MacOS)
  - System calls for thread fork, join, exit (and lock, unlock,…)
  - Kernel does context switch
  - Simple, but a lot of transitions between user and kernel mode

Multithreaded User Processes (Take 1)



Multithreaded User Processes (Take 2)

- Green threads (early Java)
  - User-level library, within a single-threaded process
  - Library does thread context switch
  - Preemption via upcall/UNIX signal on timer interrupt
  - Use multiple processes for parallelism
    - Shared memory region mapped into each process

Multithreaded User Processes (Take 3)

- Scheduler activations (Windows 8)
  - Kernel allocates processors to user-level library
  - Thread library implements context switch
  - Thread library decides what thread to run next
- Upcall whenever kernel needs a user-level scheduling decision
  - Process assigned a new processor
  - Processor removed from process
  - System call blocks in kernel

Synchronization

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

Question: Can this panic?

Thread 1

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

Thread 2

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

Why Reordering?

- Why do compilers reorder instructions?
  - Efficient code generation requires analyzing control/ data dependency
  - If variables can spontaneously change, most compiler optimizations become impossible
- Why do CPUs reorder instructions?
  - Write buffering: allow next instruction to execute while write is being completed

Fix: **memory barrier**

- Instruction to compiler/CPU
- All ops before barrier complete before barrier returns
- No op after barrier starts until barrier returns

Too Much Beer Example

	Person A	Person B
9:30	Look in fridge. Out of beer.	
9:35	Leave for store.	
9:40	Arrive at store.	Look in fridge. Out of beer.
9:45	Buy beer.	Leave for store.
9:50	Arrive home, put beer away.	Arrive at store.
9:55		Buy beer.
10:00		Arrive home, put beer away. No room!

Definitions

Race condition: output of a concurrent program depends on the order of operations between 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!)

Too Much Beer, Try #1

- Correctness property
  - Someone buys if needed (liveness)
  - At most one person buys (safety)
- Try #1: leave a note

```
if (!note)
    if (!beer) {
        leave note
        buy beer
        remove note
    }
```

Too Much Beer, Try #2

Thread A

```
leave note A
if (!note B) {
    if (!beer)
        buy beer
}
remove note A
```

Thread B

```
leave note B
if (!noteA) {
    if (!beer)
        buy beer
}
remove note B
```

Too Much Beer, Try #3

Thread A

```
leave note A
while (note B) // X
    do nothing;
if (!beer)
    buy beer;
remove note A
```

Thread B

```
leave note B
if (!noteA) {   // Y
    if (!beer)
        buy beer
}
remove note B
```

Can guarantee at X and Y that either:

(i) Safe for me to buy
(ii) Other will buy, ok to quit

Lessons

- Solution is complicated
  - “obvious” code often has bugs
- Modern compilers/architectures reorder instructions
  - Making reasoning even more difficult
- Generalizing to many threads/processors
  - Even more complex: see Peterson’s algorithm

Roadmap

Concurrent Applications

Semaphores Locks Condition Variables

Interrupt Disable Atomic Read/Modify/Write Instructions

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 (safety)
2. If no one holding, acquire gets lock (progress)
3. If all lock holders finish and no higher priority waiters, waiter eventually gets lock (progress)

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?

Too Much Beer, #4

Locks allow concurrent code to be much simpler:

```
lock.acquire();
if (!beer)
    buy beer
lock.release();
```

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
  - Beginning of procedure!
- 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!

Double Checked Locking

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

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

Single Checked Locking

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

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

Example: Bounded Buffer

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

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

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

Question

- If tryget returns NULL, do we know the buffer is empty?

- If we poll tryget in a loop, what happens to a thread calling tryput?

Condition Variables

- Waiting inside a critical section
  - Called only when holding a lock

- 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

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 is now true
   cv.signal(&lock);


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

Example: Bounded Buffer

```
get() {
    lock.acquire();
    while (front == tail) {
        empty.wait(&lock);
    }
    item = buf[front % MAX];
    front++;
    full.signal(&lock);
    lock.release();
    return item;
}
```

```
put(item) {
    lock.acquire();
    while ((tail – front) == MAX) {
        full.wait(&lock);
    }
    buf[tail % MAX] = item;
    tail++;
    empty.signal(&lock);
    lock.release();
}
```

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

empty/full are condition variables

Pre/Post Conditions

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

Question

Does the kth call to get return the kth item put?

Hint: wait must re-acquire the lock after the signaller releases it.

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

   // 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();
}
```

Rules for Condition Variables

- ALWAYS 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
  - What if wait, then release?
  - What if release, then wait?

Rules for Condition Variables, cont'd

- When a thread is woken up from wait, it may not run immediately
  - Signal/broadcast put thread on ready list
  - 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

Java Manual

When waiting upon a Condition, a “spurious wakeup” is permitted to occur, in general, as a concession to the underlying platform semantics. This has little practical impact on most application programs as a Condition should always be waited upon in a loop, testing the state predicate that is being waited for.

Structured Synchronization

- Identify objects or data structures that can be accessed by multiple threads concurrently
  - In kernel, everything!
- Add locks to object/module
  - Grab lock on start to every method/procedure
  - Release lock on finish
- If need to wait
  - while(needToWait()) { condition.Wait(lock); }
  - Do not assume when you wake up, signaller just 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

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()

Implementing Synchronization

Concurrent Applications

Semaphores Locks Condition Variables

Interrupt Disable Atomic Read/Modify/Write Instructions

Multiple Processors Hardware Interrupts

Implementing Synchronization (Take 1)

Use memory load/store instructions

- See too much beer solution/Peterson's algorithm
- Complex
- Need memory barriers
- Hard to test/verify correctness

Implementing Synchronization (Take 2)

```
Lock::acquire() {
    oldIPL = setInterrupts(OFF);
    lockHolder = myTCB;
}
Lock::release() {
    ASSERT(lockholder == myTCB);
    lockHolder = NULL;
    setInterrupts(oldIPL); // implies memory barrier
}
```

Lock Implementation, Uniprocessor

```
Lock::acquire() {
    oldIPL = setInterrupts(OFF);
    if (value == BUSY) {
        waiting.add(myTCB);
        myTCB->state = WAITING;
        next = readyList.remove();
        switch(myTCB, next);
        myTCB->state = RUNNING;
    } else {
        value = BUSY;
        lockHolder = myTCB;
    }
    setInterrupts(oldIPL);
}
```

```
Lock::release() {
    ASSERT(lockHolder == myTCB);
    oldIPL = setInterrupts(OFF);
    if (!waiting.Empty()) {
        next = waiting.remove();
        next->state = READY;
        readyList.add(next);
        lockHolder = next;
    } else {
        value = FREE;
        lockHolder = NULL;
    }
    setInterrupts(oldIPL);
}
```

What thread is currently running?

- Thread scheduler needs to know 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 variable
  - Change the value in switch
- On a multiprocessor?

What thread is currently running? (Multiprocessor Version)

- Compiler dedicates a register
  - OS/161 on MIPS: s7 points to TCB running on this CPU
- Hardware register holds processor number
  - x86 RDTSCP: read timestamp counter and processor ID
  - OS keeps an array, indexed by processor ID, listing current thread on each CPU
- Fixed-size thread stacks: put a pointer to the TCB at the bottom of its stack
  - Find it by masking the current stack pointer

Mutual Exclusion Support on a Multiprocessor

- 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
  - Implies a memory barrier
- Examples
  - Test and set // read old value, set value to 1
  - Intel: xchgb // read old value, set new value
  - Compare and swap // test if old value has changed
    // if not change it

Spinlocks

A spinlock 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, CVs

```
loop: // pointer to lock value in (%eax)
lock xchgb (%eax), 1
jnz loop
```

Spinlocks

```
Spinlock::acquire() {
  while (testAndSet(&lockValue) == BUSY)
    ;
  lockHolder = myTCB;
}
Spinlock::release() {
  ASSERT(lockHolder == myTCB);
  lockHolder = NULL;
  (void)testAndClear(&lockValue); // membarrier
}
```

Spinlocks and Interrupt Handlers

- Suppose an interrupt handler needs to access some shared data => acquires spinlock
  - To put a thread on the ready list (I/O completion)
  - To switch between threads (time slice)
- What happens if a thread holds that spinlock with interrupts enabled?
  - Deadlock is possible unless ALL uses of that spinlock are with interrupts disabled

How Many Spinlocks?

- Various data structures
  - Queue of waiting threads on lock X
  - Queue of waiting threads on lock Y
  - List of threads ready to run
- One spinlock per kernel? Bottleneck!
- One spinlock per lock
- One spinlock for the scheduler ready list
  - Per-core ready list: one spinlock per core
  - Scheduler lock requires interrupts off!

Lock Implementation, Multiprocessor

```
Lock::acquire() {
   spinLock.acquire();
   if (value == BUSY) {
      waiting.add(myTCB);
      suspend(&spinlock);
      ASSERT(lockHolder ==
                   myTCB);
   } else {
      value = BUSY;
      lockHolder = myTCB;
   }
   spinLock.release();
}
```

```
Lock::release() {
   ASSERT(lockHolder = myTCB);
   spinLock.acquire();
   if (!waiting.Empty()) {
      next = waiting.remove();
      lockHolder = next;
      sched.makeReady(next);
   } else {
      value = FREE;
      lockHolder = NULL;
   }
   spinLock.release();
}
```

Lock Implementation, Multiprocessor

```
Sched::suspend(SpinLock *sl) {
    TCB *next;
    oldIPL = setInterrupts(OFF);
    schedSL.acquire();
    sl–>release();
    myTCB–>state = WAITING;
    next = readyList.remove();
    switch(myTCB, next);
    myTCB–>state = RUNNING;
    schedSL.release();
    setInterrupts(oldIPL);
}
```

```
Sched::makeReady(TCB
    *thread) {
    oldIPL =setInterrupts(OFF);
    schedSL.acquire();
    readyList.add(thread);
    thread–>state = READY;
    schedSL.release();
    setInterrupts(oldIPL);
}
```

Lock Implementation, Linux

- Most locks are free most of the time. Why?
  - Linux implementation takes advantage of this fact
- Fast path
  - If lock is FREE and no one is waiting, two instructions to acquire the lock
  - If no one is waiting, two instructions to release
- Slow path
  - If lock is BUSY or someone is waiting (see multiproc)
- Two versions: one with interrupts off, one w/o

Lock Implementation, Linux

```
struct mutex {
 /* 1: unlocked ; 0: locked;
    negative : locked,
    possible waiters */
 atomic_t count;
 spinlock_t wait_lock;
 struct list_head wait_list;
};
```

```
// atomic decrement
// %eax is pointer to count
lock decl (%eax)
jns 1f // jump if not signed
          // (if value is now 0)
call slowpath_acquire
1:
```

Application Locks

- A system call for every lock acquire/release?
  - Context switch in the kernel!
- Instead:
  - Spinlock at user level
  - "Lazy" switch into kernel if spin for period of time
- Or scheduler activations:
  - Thread context switch at user level

Readers/Writers Lock

- A common variant for mutual exclusion
  - One writer at a time, if no readers
  - Many readers, if no writer
- How might we implement this?
  - ReaderAcquire(), ReaderRelease()
  - WriterAcquire(), WriterRelease()
  - Need a lock to keep track of shared state
  - Need condition variables for waiting if readers/writers are in progress
  - Some state variables

Readers/Writers Lock

```
Lock lock = FREE
CV okToRead = nil
CV okToWrite = nil
AW = 0  //active writers
AR = 0   // active readers
WW = 0 // waiting writers
WR = 0  // waiting readers
```

Readers/Writers Lock

```
ReaderAcquire()
    lock.Acquire();
    while (AW > 0) {
        WR++;
        okToRead.wait(&lock);
        WR--;
```

```
Lock lock = FREE

CV okToRead = nil
CV okToWrite = nil

AW = 0
AR =  0
WW = 0
WR = 0
```

```
lock.Acquire();
while (AW > 0 || WW > 0) {
   WR++;
   okToRead.wait(&lock);
   WR--;
}
AR++;
lock.Release();

Read data

lock.Acquire();
AR--;
if (AR == 0 && WW > 0)
  okToWrite.Signal();
lock.Release();
```

```
lock.Acquire();
while (AW > 0 || AR > 0) {
   WW++;
   okToRead.wait(&lock);
   WW--;
}
AW++;
lock.Release();

Write data

lock.Acquire();
AW--;
if (WW > 0)
  okToWrite.Signal();
else if (WR > 0)
 okToRead.Signal();
lock.Release();
```

Readers/Writers Lock

- Can readers starve?
  - Yes: writers take priority
- Can writers starve?
  - Yes: a waiting writer may not be able to proceed, if another writer slips in between signal and wakeup

Readers/Writers Lock, w/o Starvation
Take 1

```
Writer() {
 lock.Acquire();
 // check if another thread is already waiting
 while ((AW + AR + WW) > 0) {
      WW++;
      okToWrite.Wait(&lock);
      WW--;
  }
 AW++;
 lock.Release();
```

Readers/Writers Lock w/o Starvation Take 2

```
// check in
lock.Acquire();
myPos = numWriters++;
while ((AW + AR > 0 ||
        myPos > nextToGo) {
    WW++;
    okToWrite.Wait(&lock);
    WW--;
}
AW++;
lock.Release();
```

```
// check out
lock.Acquire();
AW--;
nextToGo++;
if (WW > 0) {
  okToWrite.Signal(&lock);
} else if (WR > 0)
   okToRead.Bcast(&lock);
lock.Release();
```

Readers/Writers Lock w/o Starvation
Take 3

```
// check in
lock.Acquire();
myPos = numWriters++;
myCV = new CV;
writers.Append(myCV);
while ((AW + AR > 0 ||
          myPos > nextToGo) {
   WW++;
   myCV.Wait(&lock);
   WW--;
}
AW++;
delete myCV;
lock.Release();
```

```
// check out
lock.Acquire();
AW--;
nextToGo++;
 if (WW > 0) {
      cv = writers.Front();
      cv.Signal(&lock);
 } else if (WR > 0)
      okToRead.Broadcast(&lock);
lock.Release();
```

Mesa vs. Hoare semantics

- Mesa
  - Signal puts waiter on ready list
  - Signaller keeps lock and processor
- Hoare
  - Signal gives processor and lock to waiter
  - When waiter finishes, processor/lock given back to signaller
  - Nested signals possible!

FIFO Bounded Buffer (Hoare semantics)

```
get() {
    lock.acquire();
    if (front == tail) {
        empty.wait(&lock);
    }
    item = buf[front % MAX];
    front++;
    full.signal(&lock);
    lock.release();
    return item;
}
```

```
put(item) {
    lock.acquire();
    if ((tail – front) == MAX) {
        full.wait(&lock);
    }
    buf[last % MAX] = item;
    last++;
    empty.signal(&lock);
  // CAREFUL: someone else ran
    lock.release();
}
```

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

empty/full are condition variables

FIFO Bounded Buffer (Mesa semantics)

- Create a condition variable for every waiter
- Queue condition variables (in FIFO order)
- Signal picks the front of the queue to wake up
- CAREFUL if spurious wakeups!

- Easily extends to case where queue is LIFO, priority, priority donation, …
    - With Hoare semantics, not as easy

FIFO Bounded Buffer (Mesa semantics, put() is similar)

```
get() {
    lock.acquire();
    myPosition = numGets++;
    self = new Condition;
    nextGet.append(self);
    while (front < myPosition
            || front == tail) {
      self.wait(&lock);
    }
    delete self;
    item = buf[front % MAX];
    front++;
    if (next = nextPut.remove()) {
        next->signal(&lock);
    }
    lock.release();
    return item;
}
```

Initially: front = tail = numGets = 0; MAX is buffer capacity

nextGet, nextPut are queues of Condition Variables

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/wakeup: interrupt handler, fork/join

Semaphore Implementation

```
Semaphore::P() {
    oldIPL=setInterrupts(OFF);
    spinLock.acquire();
    if (value == 0) {
        waiting.add(myTCB);
        suspend(&spinlock);
    } else {
        value--;
    }
    spinLock.release();
    setinterrupts(oldIPL);
}
```

```
Semaphore::V() {
    oldIPL=setInterrupts(OFF);
    spinLock.acquire();
    if (!waiting.Empty()) {
        next = waiting.remove();
        sched.makeReady(next);
    } else {
       value++;
    }
    spinLock.release();
    setInterrupts(oldIPL);
}
```

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 (Take 1)

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

Implementing Condition Variables using Semaphores (Take 2)

```
wait(lock) {
    lock.release();
    semaphore.P();
    lock.acquire();
}
signal() {
    if (semaphore is not empty)
        semaphore.V();
}
```

Implementing Condition Variables using Semaphores (Take 3)

```
wait(lock) {
    semaphore = new 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
    }
}
```

Communicating Sequential Processes (CSP/Google Go)

- Threads communicate through channels
  - Bounded buffer: put/get
- Good match for data flow processing
  - Producer/consumer
- No memory races!

CSP/Google Go

- What about general computation?
  - Is CSP as powerful as locks/condition variables?
- A thread per shared object
  - Only thread allowed to touch object's data
  - To call a method on the object, send thread a message with method name, arguments
  - Thread waits in a loop, get msg, do operation

Bounded Buffer (CSP)

```
while (cmd = getNext()) {
  if (cmd == GET) {
    if (front < tail) {
      // do get
      // send reply
      // if pending put, do it
      // and send reply
    } else
      // queue get operation
  }
  } else { // cmd == PUT
    if ((tail – front) < MAX) {
      // do put
      // send reply
      // if pending get, do it
      // and send reply
    } else
      // queue put operation
}
```

Locks/CVs vs. CSP

- Create a lock on shared data
  = create a single thread to operate on data
- Call a method on a shared object
  = send a message/wait for reply
- Wait for a condition
  = queue an operation that can't be completed just yet
- Signal a condition
  = perform a queued operation, now enabled

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()