Synchronization 2: Lock Implementation

Lecture 8

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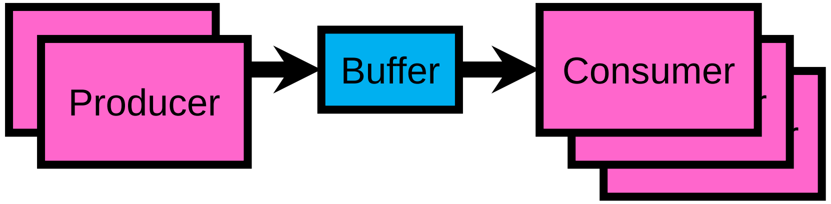
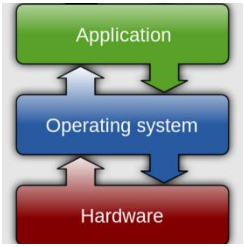
https://teaching.hkaiser.org/spring2025/csc4103/

Recall: Producer-Consumer

- 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

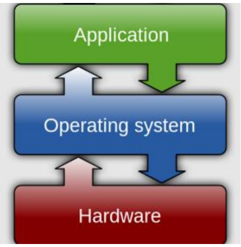


Recall: Producer-Consumer (Semaphores)

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

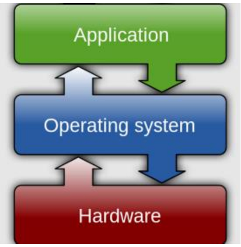
```
Producer(item) {
  freeSlots.P();
  mutex.acquire();
  Enqueue(item);
  mutex.release();
  usedSlots.V();
}
```

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



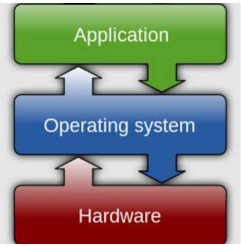
Recall: Problems with Semaphores

- 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



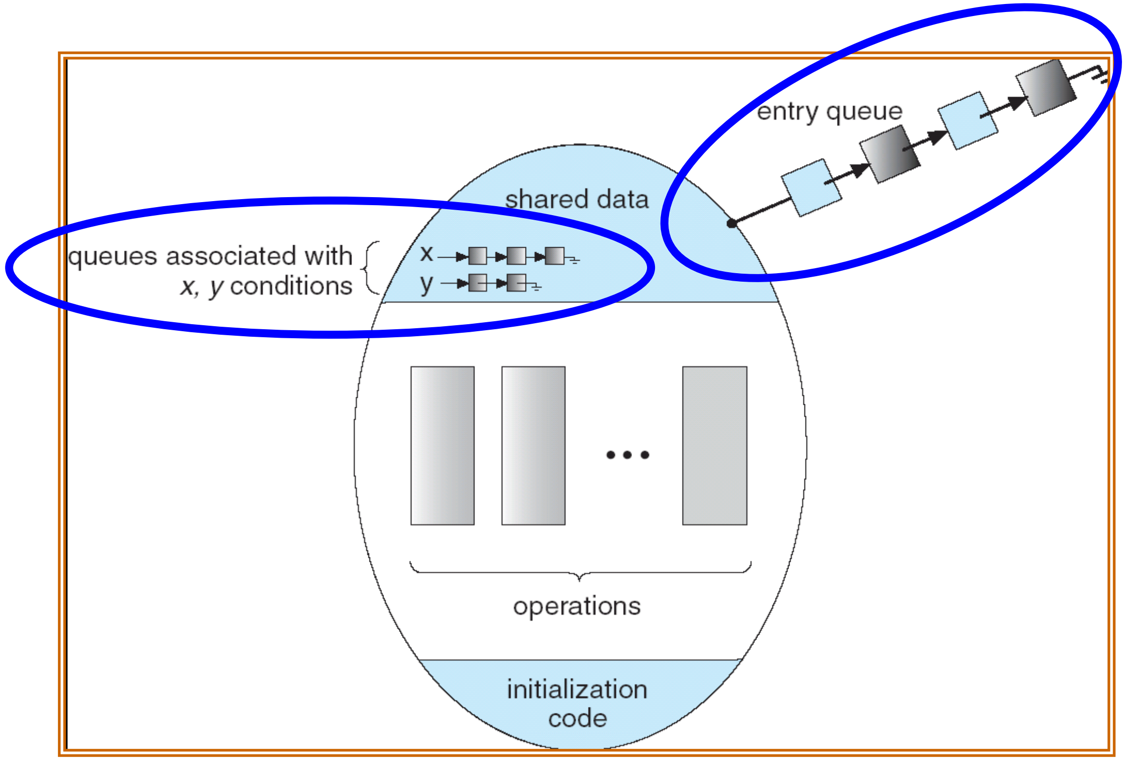
Recall: Condition Variables

- 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

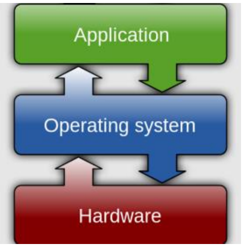


Recall: Monitors

- 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



Recall: Mesa Monitors vs. Hoare Monitors

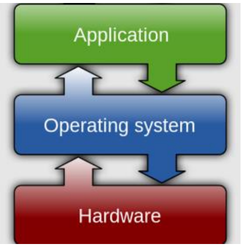
Mesa Monitor

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

Hoare Monitor

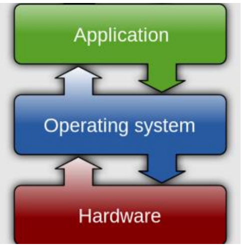
```
if (buffer empty) {
  cond_wait(&not_empty, &buf_lock);
}
```

- In practice, almost all OSes implement Mesa monitors



Recall: 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!



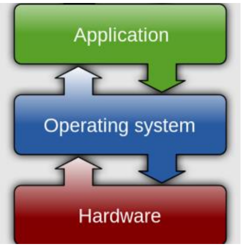
Concurrency and Synchronization in C

- 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();
}
```

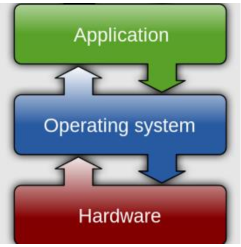


C++ Lock Guards

```
#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
}
```



Today: How to implement synchronization primitives?

For now, just consider locks inside the kernel.

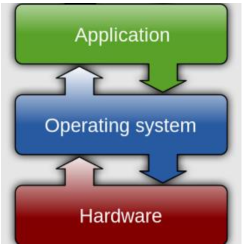
Recall: Race Conditions

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

Thread A	Thread B
`x += 1;`	`x += 1;`

Thread A	Thread B
`ld r1, &x`	
	`ld r1, &x`
	`add r1, r1, 1`
	`st r1, &x`
`add r1, r1, 1`	
`st r1, &x`	

- 1 or 2 (non-deterministic)

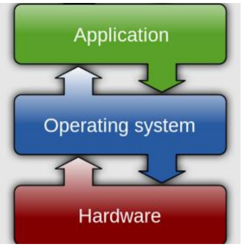


Recall: Race Conditions

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

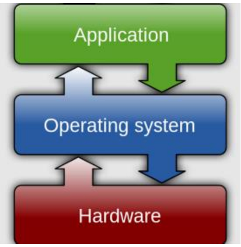
Thread A	Thread B
`x = 0x1;`	`x = 0x400;`

- `0x1` or `0x400` (non-deterministic)
  - Note: on some architectures (ARM) we could see 0x401



Atomic Operations

- To understand a concurrent program, we need to know what the underlying indivisible operations are!
- Atomic Operation: an operation that always runs to completion or not at all
  - It is indivisible: it cannot be stopped in the middle and state cannot be modified by someone else in the middle
  - It is thread-safe by design
- On most machines, memory references and assignments (i.e. loads and stores) of words are atomic
- On other architectures (ARM!) load/store of a byte is atomic



Concurrency is Hard!

- Even for practicing engineers trying to write mission-critical, bulletproof code!
  - Threaded programs must work for all inter-leavings of thread instruction sequences
  - Cooperating threads inherently non-deterministic and non-reproducible
  - Really hard to debug unless carefully designed!
- Therac-25: Radiation Therapy Machine with Unintended Overdoses
- Mars Pathfinder Priority Inversion (JPL Account)
- Toyota Uncontrolled Acceleration (CMU Talk)
  - 256.6K Lines of C Code, ~9-11K global variables
  - Inconsistent mutual exclusion on reads/writes

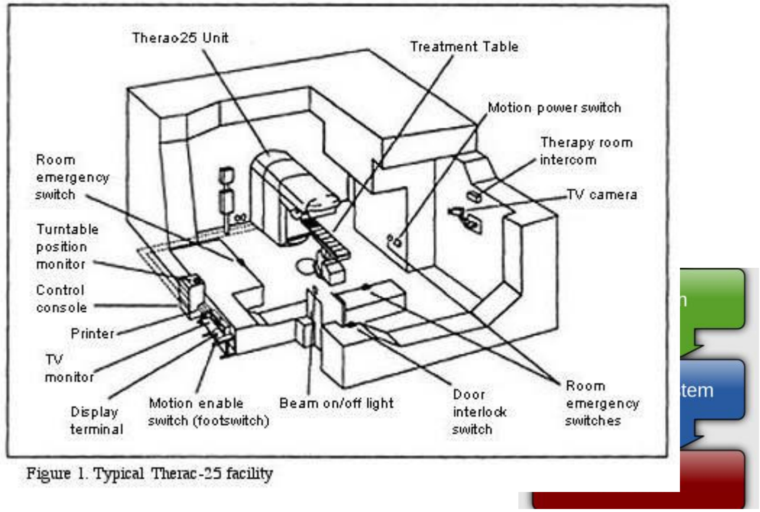
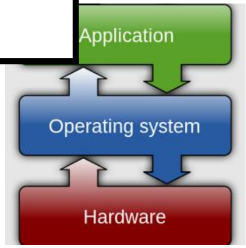


Figure 1. Typical Therac-25 facility

Motivating Example: "Too Much Milk"

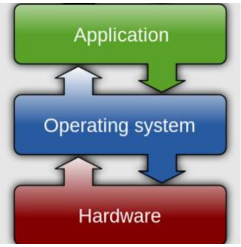
- Analogy between problems in OS and problems in real life
- Example: People need to coordinate:

Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away



Too Much Milk: Correctness

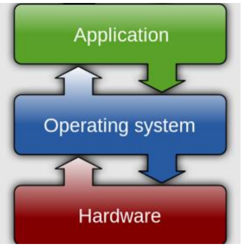
- Safety: At most one person buys milk.
- Liveness: If milk is needed, at least one person buys it.



Attempt #1

- Leave a note
  - Place on fridge before buying
  - Remove after buying
  - Don't go to store if there's already a note
- Leaving/checking a note is atomic (word load/store)

```
if (noMilk) {
  if (noNote) {
    leave Note;
    buy milk;
    remove Note;
  }
}
```



Attempt #1 in Action

Thread A

```
if (noMilk) {
  if (noNote) {


    leave Note;
    buy milk;
    remove Note;
  }
}
```

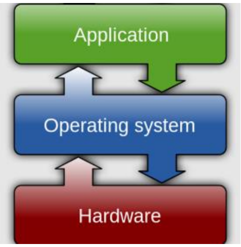
Thread B

```
if (noMilk) {
  if (noNote) {




    leave Note;
    buy milk;
    remove note;
  }
}
```

Achieves liveness but not safety

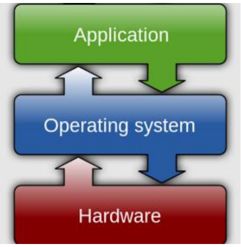


Attempt #1.5

- Idea: leave note, then check for milk

```
leave Note;
if (noMilk) {
  if (noNote) {
    buy milk;
  }
}
remove Note;
```

But there's always a note – you just left one!



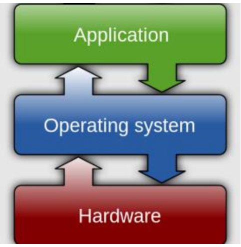
Attempt #2: Use Named Notes

Thread A

```
leave note A
if (noMilk) {
  if (noNote B) {
    buy milk
  }
}
remove note A
```

Thread B

```
leave note B
if (noMilk) {
  if (noNote A) {
    buy milk
  }
}
remove note B
```



Attempt #2 in Action

Thread A

```
leave note A
if (noMilk) {

  if (noNote B) {
    buy milk
  }
}







remove note A
```

Thread B

```

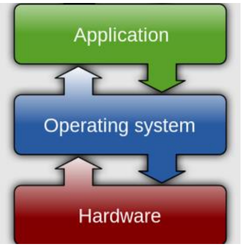

leave note B





if (noMilk) {
  if (noNote A) {
    buy milk
  }
}
remove note B
```

Achieves safety but not liveness



Attempt #3: Wait

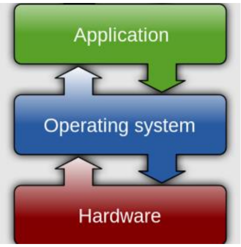
Thread A

```
leave note A
while (note B) {
  do nothing
}
if (noMilk) {
  buy milk
}
remove note A
```

Thread B

```
leave note B
while (note A) {
  do nothing
}
if (noMilk) {
  buy milk
}
remove note B
```

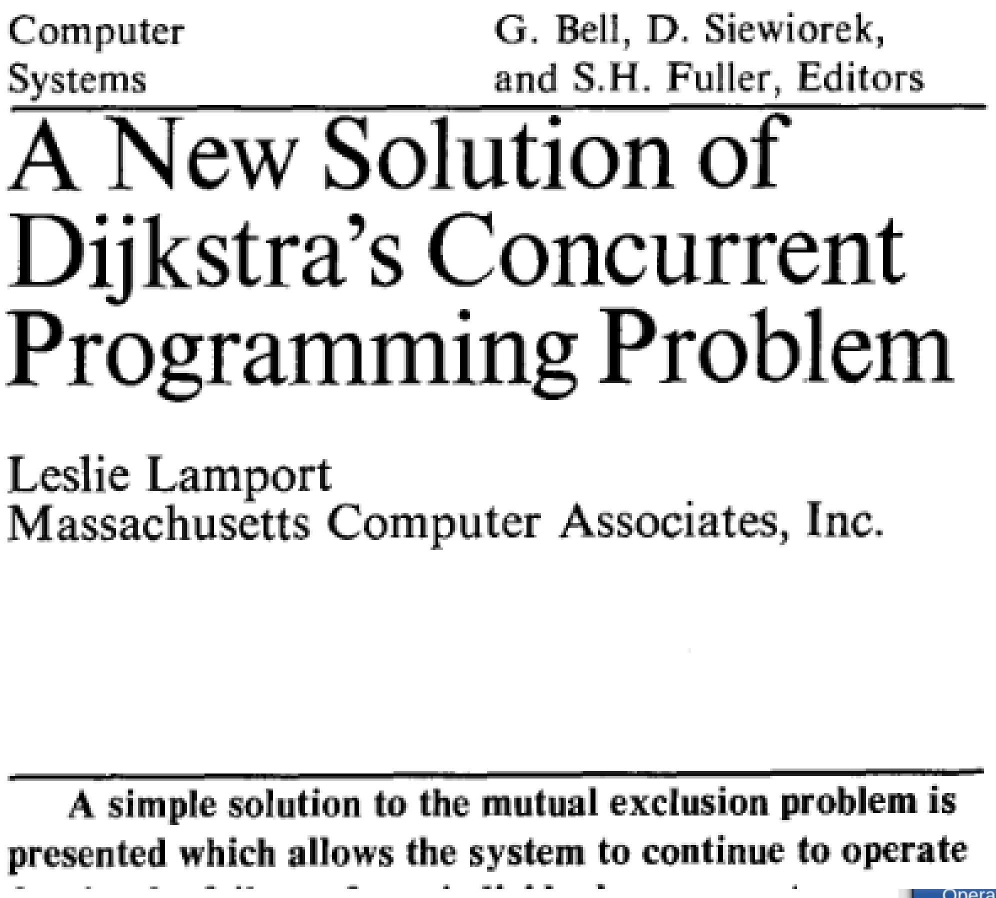
This is a correct solution!



This Generalizes to *n* Threads…

- Leslie Lamport's "Bakery Algorithm" (1974)
- Allows one to protect a critical section like:

```
if (noMilk) {
  buy milk;
}
```

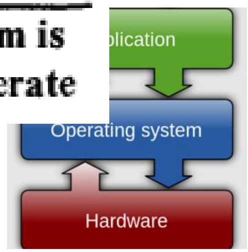

Computer Systems

G. Bell, D. Siewiorek, and S.H. Fuller, Editors

A New Solution of Dijkstra's Concurrent Programming Problem

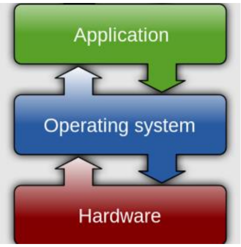
Leslie Lamport
Massachusetts Computer Associates, Inc.

A simple solution to the mutual exclusion problem is presented which allows the system to continue to operate



Solution #3 Discussion

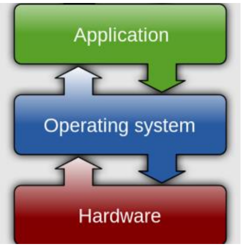
- Solution #3 works, but it's not great
  - Really complex – even for this simple example
    - Hard to convince yourself that this really works
  - While a thread is waiting, it is consuming CPU time
    - This is called "busy-waiting"
- There's a better way
  - Have hardware provide more primitives than simple atomic load & store
  - Build even higher-level programming abstractions on this hardware support
    - Make sure the OS scheduler never allows another thread to enter the critical section
    - The other thread becomes blocked if it tries to enter



Where are we going with Synchronization?

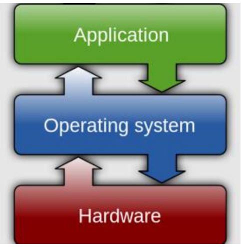
- Building an efficient, easy-to-use API

Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap



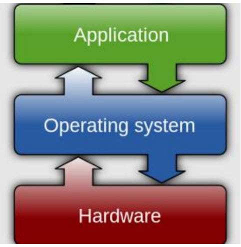
Announcements

- Project 1 design document due March 10
  - You have started talking to the TA, hopefully
- Assignment 2 now published, due April 7
- Project 1 due March 24
- Mid-term examination March 12, 5.00pm, 1200 PFT
  - Mid-term review March 10



Implementing Locks: Single Core

- How can we make `lock.Acquire()` and `lock.Release()` appear atomic to other threads?
- Idea: A context switch can only happen (assuming threads don't yield) if there's an interrupt
- "Solution": Disable interrupts while holding lock
- x86 has cli and sti instructions that only operate in system mode (PL=0)
  - Interrupts enabled bit in FLAGS register



Naïve Interrupt Enable/Disable

```
Acquire() {
  disable interrupts;
}
```

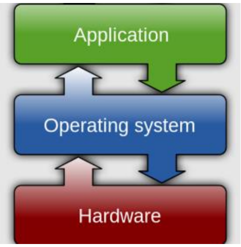
```
Release() {
  enable interrupts;
}
```

- Problem: can stall the entire system

```
Lock.Acquire()
While (1) {}
```

- Problem: What if we want to do I/O?

```
Lock.Acquire()
Read from disk
/* OS waits for (disabled) interrupt! */
```



Implementing Locks: Single Core

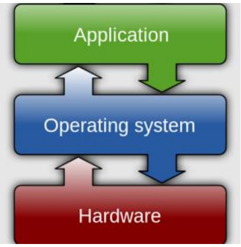
```
int value = FREE;

Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    run_new_thread();
    // Enable interrupts?
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

```
Release() {
  disable interrupts;
  if (anyone on wait queue) {
    take thread off wait queue;
    Place on ready queue;
  }

  value = FREE;
  enable interrupts;
}
```

- Key idea: maintain a lock variable (**`value`**) and disable interrupts only during operations on that variable



Discussion

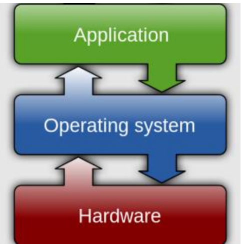
- Why do we need to disable interrupts at all?
  - Avoid interruption between checking and setting lock value
  - Otherwise two threads could think that they both have lock

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      run_new_thread();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

Critical Section (the block from `if (value == BUSY)` through the closing `}` of the else)

- Disabling interrupts prevents preemption
- Locks disable interrupts to provide *another* critical section

- Unlike the naïve solution, interrupts are disabled for a short time only



Implementing Locks: Single Core

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int value = FREE;
Acquire() {
  disable interrupts;
  if (value == BUSY) {
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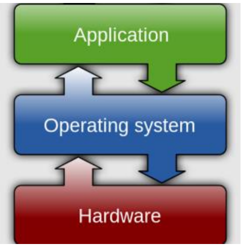
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

```
Release() {
  disable interrupts;
  if (anyone on wait queue) {
    take thread off wait queue;
    Place on ready queue;
  }

  value = FREE;
  enable interrupts;
}
```

- Key idea: maintain a lock variable (**`value`**) and disable interrupts only during operations on that variable



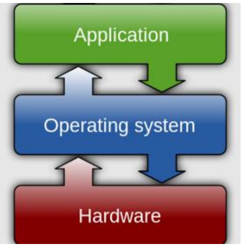
Re-enabling Interrupts when Waiting

enable interrupts →

enable interrupts →

```
Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    run_new_thread()
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

- Before on the queue?
  - Release might not wake up this thread!
- After putting the thread on the queue?
  - Gets woken up, but immediately switches away

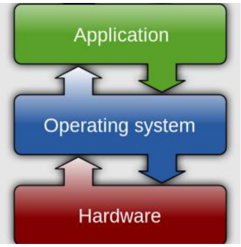


Re-enabling Interrupts when Waiting

enable interrupts →

```
Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    run_new_thread()
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

- Best solution: after the current thread suspends
- How?
  - `run_new_thread()` should do it!
  - Part of returning from `switch()`



How to Re-enable Interrupts when Waiting

- In scheduler, since interrupts are disabled when switching threads:
  - Responsibility of the next thread is to re-enable interrupts
  - When the sleeping thread wakes up, returns and re-enables interrupts

Thread A

```
...
disable ints
call run_new_thread
```

context switch →

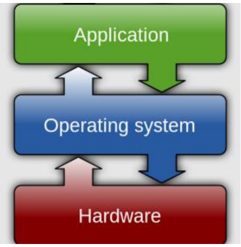
Thread B

```
run_new_thread returns
enable ints
...
disable ints
call run_new_thread
```

← context switch

Thread A

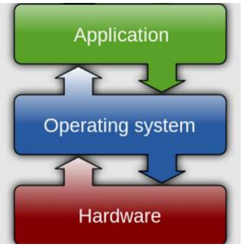
```
run_new_thread returns
enable ints
...
```



Enabling Interrupts vs. Restoring Interrupts

- 99% of the time, you want to restore interrupts, not enable them
- We used "enable interrupts" in this lecture since we were assuming interrupts are enabled when acquiring the lock
- In PintOS:

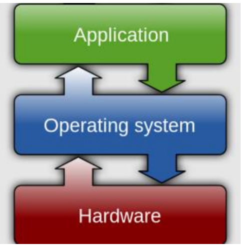
```
enum intr_level state = intr_disable();
<code manipulating shared data>
intr_set_level(state);
```



When does this Lock Implementation Work?

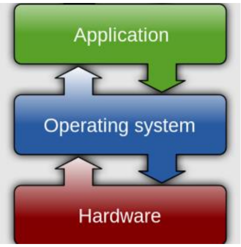
- Answer: For threads in the kernel on a single-core machine.

- What about multi-core machines?
- What about user threads?



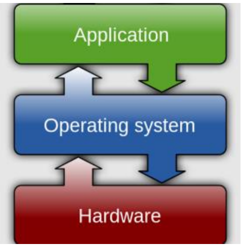
Multi-Core Machines

- How to synchronize with threads executing in parallel on other cores?
  - Disable interrupts on all cores?
  - Prevent other cores from making progress?
- Implement locks in hardware?
  - What's the interface between hardware lock and OS scheduler?
- Solution: Use hardware support for atomic operations



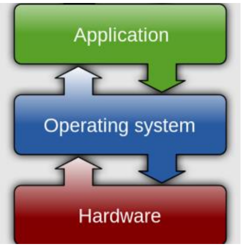
Atomic Operations

- Definition: An operation runs to completion or not at all
  - Foundation for synchronization primitives
- Example: Loading or storing a word (on most modern architectures)



Atomic Read-Modify-Write Instructions

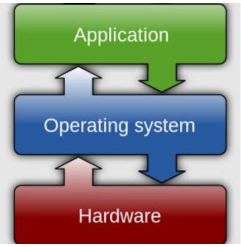
- These instructions read a value and write a new value atomically
- Hardware is responsible for implementing this correctly
  - On both uniprocessors (not too hard)
  - And multiprocessors (requires help from cache coherence protocol)
- Unlike disabling interrupts, can be used on both uniprocessors and multiprocessors
- Natural extensions to user-level locking



Examples of Read-Modify Write

```
test&set (&address) {              /* most architectures */
    result = M[address];           // return result from "address" and
    M[address] = 1;                // set value at "address" to 1
    return result;
}

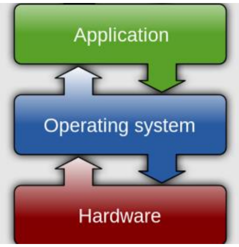
swap (&address, register) {        /* x86 */
    temp = M[address];             // swap register's value to
    M[address] = register;         // value at "address"
    register = temp;
}
```



Examples of Read-Modify Write

```
compare&swap (&address, reg1, reg2) {      /* 68000, x86 */
    if (reg1 == M[address]) {   // If memory still == reg1,
        M[address] = reg2;      // then  put reg2 => memory
        return success;
    } else {                    // Otherwise do not change memory
        return failure;
    }
}


load-linked&store-conditional(&address) { /* R4000, alpha */
  loop:
    ll r1, M[address];
    movi r2, 1;                 // Can do arbitrary computation
    sc r2, M[address];
    beqz r2, loop;
}
```

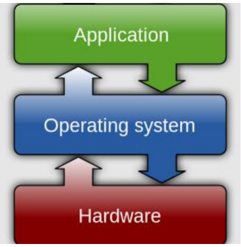


Implementing Locks with test&set

- Simple, but flawed, solution:

```
int value = 0; // Free
Acquire() {
  while (test&set(value)) {}; // spin while busy
}
Release() {
  value = 0;                  // atomic store
}
```

- Explanation:
  - If lock is free, test&set reads 0 and sets value=1, so lock is now busy. It returns 0 so while exits.
  - If lock is busy, test&set reads 1 and sets value=1 (no change). It returns 1, so while loop continues.
  - When we set value = 0, someone else can get lock.
- Busy-Waiting: thread consumes cycles while waiting
- For multiprocessor cache coherence: every test&set() is a write, which makes value ping-pong around in cache (using lots of memory BW)

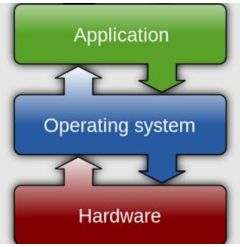


This is Called a Spinlock

- Spinlock implementation:

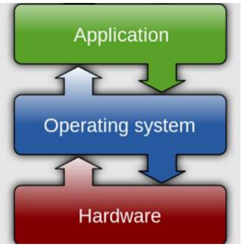
```
int value = 0; // Free
Acquire() {
  while (test&set(value)) {}; // spin while busy
}
Release() {
  value = 0;                  // atomic store
}
```

- Spinlock doesn't put the calling thread to sleep --- it just busy waits



Problem: Busy-Waiting for Lock

- Positives for this solution
  - Machine can receive interrupts
  - User code can use this lock (poorly)
  - Works on a multiprocessor
- Negatives
  - Very inefficient: thread will consume cycles waiting
  - Waiting thread takes cycles away from thread holding lock (no one wins!)
  - Priority Inversion: If busy-waiting thread has higher priority than thread holding lock $\Rightarrow$ no progress!
- For semaphores (and monitors), waiting thread may wait for an arbitrary long time!
  - Thus even if busy-waiting was OK for locks, definitely not OK for other primitives
  - Homework/exam solutions should avoid busy-waiting!



Better Locks Using test&set

- Can we build test&set locks without busy-waiting?
  - Can't entirely, but can minimize!
  - Idea: only busy-wait to atomically check lock value

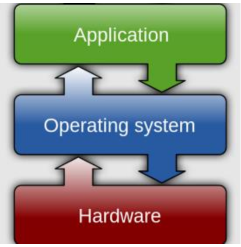
```
int guard = 0;
int value = FREE;

Acquire() {
    // Short busy-wait time
    while (test&set(guard)) /**/;
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread() & guard = 0;
    } else {
        value = BUSY;
        guard = 0;
    }
}
```

```
Release() {
    // Short busy-wait time
    while (test&set(guard)) /**/;
    if anyone on wait queue {
        take thread off wait queue
        Place on ready queue;
    }

    value = FREE;
    guard = 0;
}
```

- Note: sleep has to be sure to reset the guard variable
  - Why can't we do it just before or just after the sleep?



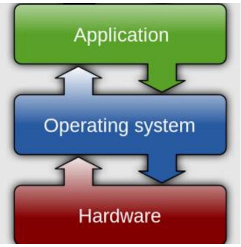
Alternative View: Bootstrapping a Spinlock

```
SpinLock guard = FREE;
int value = FREE;

Acquire() {
    // Short busy-wait time
    guard.Acquire();
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread() & guard.Release();
    } else {
        value = BUSY;
        guard.Release();
    }
}
```

```
Release() {
    // Short busy-wait time
    guard.Acquire();
    if anyone on wait queue {
        take thread off wait queue
        Place on ready queue;
    }

    value = FREE;
    guard.Release();
}
```



Comparison to Disabling Interrupts

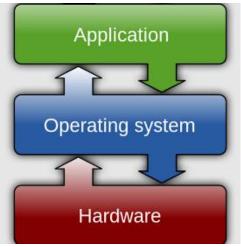
```
int value = FREE;

Acquire() {
    // Short busy-wait time
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        run_new_thread();
      // scheduler enables interrupts
    } else {
        value = BUSY;
        enable interrupts;
    }
}
```

```
Release() {
    disable interrupts;
    if anyone on wait queue {
        take thread off wait queue
        Place on ready queue;
    }

    value = FREE;
    enable interrupts;
```

- We changed disable interrupts → spinlock.Acquire() [while (test&set(guard)]
- We changed enable interrupts → spinlock.Release() [guard = 0]



Recap: Locks Using Interrupts

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

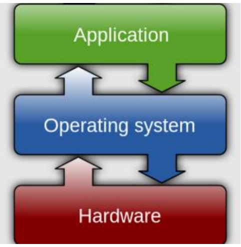
```
Acquire() {
  disable interrupts;
}
```

```
Release() {
  enable interrupts;
}
```

Threads waiting to enter critical section busy-wait

```
int value = 0;
Acquire() {
  // Short busy-wait time
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() & disable interrupts;
  } else {
    value = 1;
    guard = 0;
  }
}
```

```
Release() {
  // Short busy-wait time
  disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  }
  value = 0;
  enable interrupts;
}
```



Recap: Locks Using test&set

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

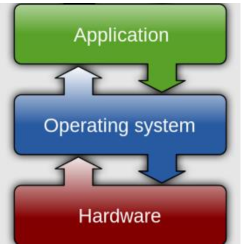
```
int value = 0;
Acquire() {
  while(test&set(value));
}

Release() {
  value = 0;
}
```

Threads waiting to enter critical section busy-wait

```
int guard = 0;
int value = 0;
Acquire() {
  // Short busy-wait time
  while(test&set(guard));
  if (value == 1) {
    put thread on wait-queue;
    go to sleep()& guard = 0;
  } else {
    value = 1;
    guard = 0;
  }
}
```

```
Release() {
  // Short busy-wait time
  while (test&set(guard));
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  }
  value = 0;
  guard = 0;
}
```

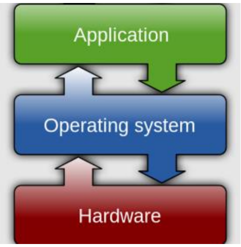


Recall: Spinlock

- Spinlock implementation:

```
int value = 0; // Free
Acquire() {
  while (test&set(value)) {}; // spin while busy
}
Release() {
  value = 0;                  // atomic store
}
```

- Spinlock doesn't put the calling thread to sleep—it just busy waits
  - When might this be preferable?
- For multiprocessor cache coherence: every test&set() is a write, which makes value ping-pong around in cache (using lots of memory BW)



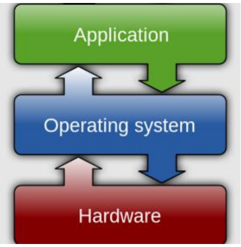
Better Spinlock: test&test&set

- A better spinlock solution:

```
int mylock = 0; // Free
Acquire() {
  do {
    while(mylock) /**/;        // Wait until might be free
  } while(test&set(&mylock)); // exit if get lock
}

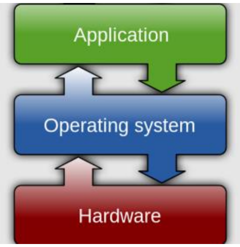
Release() {
  mylock = 0;
}
```

- Explanation:
  - Wait until lock might be free (only reading – stays in cache)
  - Then, try to grab lock with test&set
  - Repeat if fail to actually get lock
- Busy-Waiting: no longer impacts other processors!



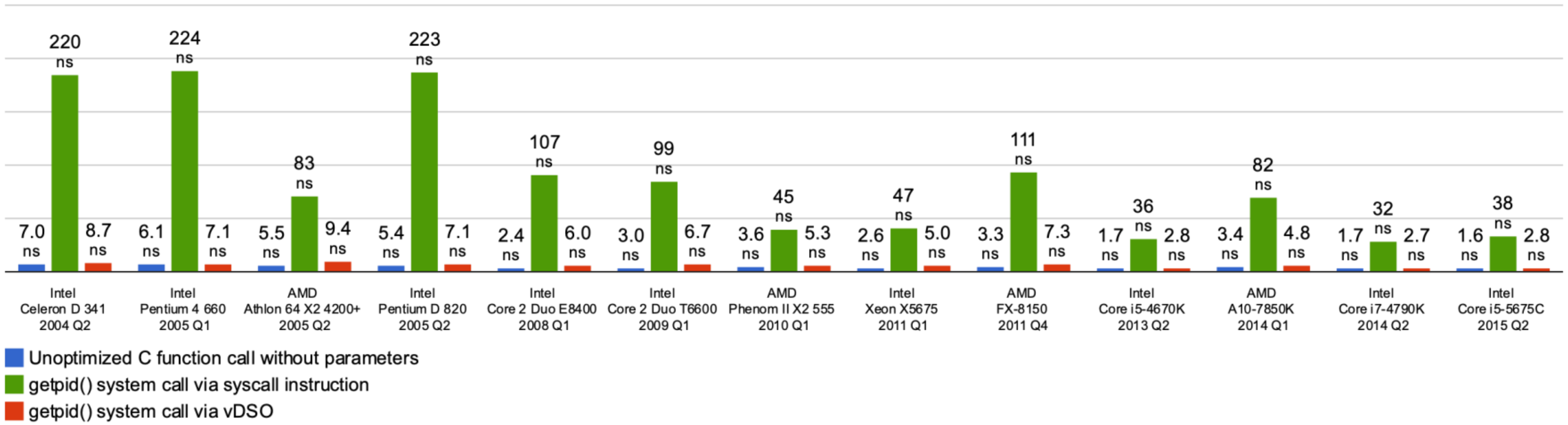
Locks in Userspace?

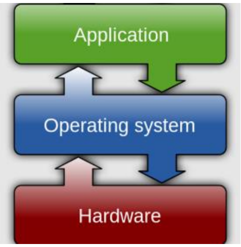
- We’ve looked at locks in the kernel
  - Uniprocessor case (disable interrupts)
  - Multiprocessor case (test&set)
- What about locks in userspace?
- Spinlocks just work
- Simple idea for non-busy-waiting lock:
  - For each userspace lock, allocate a lock in the kernel
  - Make a syscall for each acquire/release operation to acquire the lock in the kernel



Recall: Overhead of Syscalls

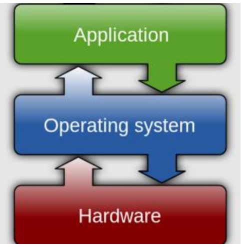
- Syscalls are 25x more expensive than function calls (~100 ns)
- read/write a file byte by byte? Max throughput of ~10MB/second
- With fgetc? Keeps up with your SSD





Userspace Locks: Syscall Overhead

- Can we avoid syscall overhead when acquiring a non-busy-waiting lock in userspace?
  - No: can't put a thread to sleep (i.e., block the thread) without entering the kernel
- What we can do: avoid system calls in the uncontended case (i.e., the case where we can acquire the lock without blocking)
  - Helps both uniprocessor case and multiprocessor case

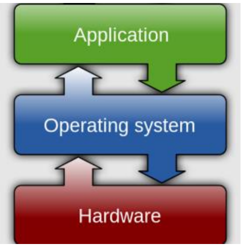


Linux futex: Fast Userspace Mutex

```
#include <linux/futex.h>
#include <sys/time.h>

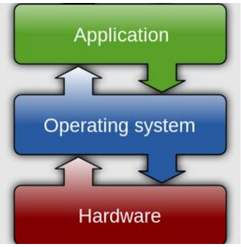
int futex(int *uaddr, int futex_op, int val,
      const struct timespec *timeout );
```

- `uaddr` points to a 32-bit value in user space
- `futex_op`
  - `FUTEX_WAIT` – if val == *uaddr sleep till `FUTEX_WAKE`
    - Atomic check that condition still holds
  - `FUTEX_WAKE` – wake up at most `val` waiting threads
  - `FUTEX_FD`, `FUTEX_WAKE_OP`, `FUTEX_CMP_REQUEUE`
- `timeout`
  - `ptr` to a `timespec` structure that specifies a timeout for the op
    - NULL == wait forever



Linux futex: Fast Userspace Mutex

- Idea: Userspace lock is syscall-free in the uncontended case
- Lock has three states
  - Free (no syscall when acquiring lock)
  - Busy, no waiters (no syscall when releasing lock)
  - Busy, possibly with some waiters
- `futex` is not exposed in libc; it is used within the implementation of `pthreads`



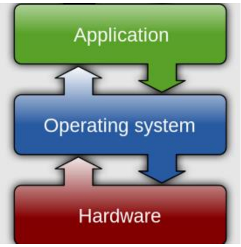
Example: Userspace Locks with futex

```
int value = 0; // free
bool maybe_waiters = false;

Acquire() {
    while (test&set(value)) {
        maybe_waiters = true;
        futex(&value, FUTEX_WAIT, 1);
        // futex: sleep if lock is acquired
        maybe_waiters = true;
    }
}
```

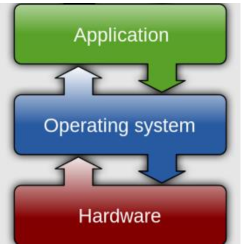
```
Release() {
    value = 0;
    if (maybe_waiters) {
        maybe_waiters = false;
        futex(&value, FUTEX_WAKE, 1);
        // futex: wake up a sleeping thread
    }
}
```

- This is syscall-free in the uncontended case
  - Temporarily falls back to syscalls if multiple waiters, or concurrent acquire/release
- But it can be considerably optimized!
  - See "Futexes are Tricky" by Ulrich Drepper



Conclusion

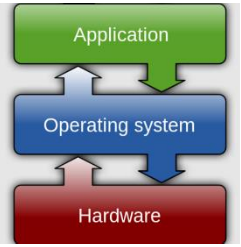
- Important concept: Atomic Operations
  - An operation that runs to completion or not at all
  - These are the primitives on which to construct various synchronization primitives
- Talked about hardware atomicity primitives:
  - Disabling of Interrupts, test&set, swap, compare&swap, load-locked & store-conditional
- Showed several constructions of Locks
  - Must be very careful not to waste/tie up machine resources
    - Shouldn't disable interrupts for long
    - Shouldn't spin wait for long
  - Key idea: Separate lock variable, use hardware mechanisms to protect modifications of that variable



Bonus Slides (If Time)

Further Reducing Overhead

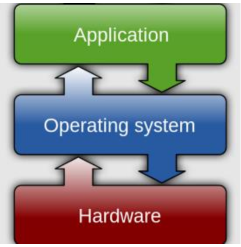
- Make locks less contended [how?]
- Move synchronization and scheduling into userspace



We've Looked At: Kernel-Supported Threads

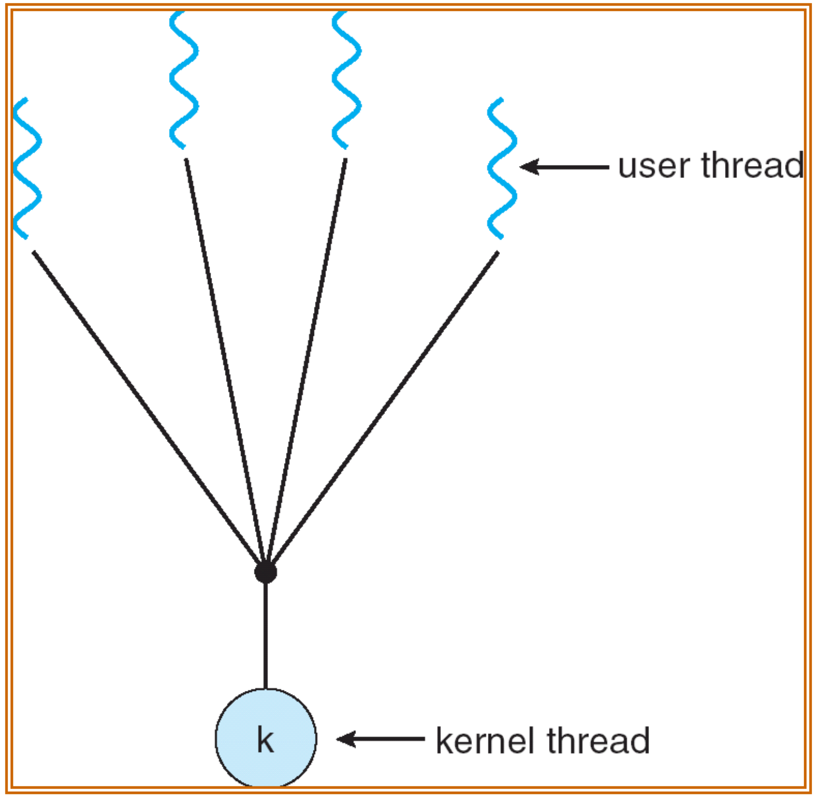
- Threads run and block (e.g., on I/O) independently
- One process may have multiple threads waiting on different things
- Two mode switches for every context switch (expensive)
- Create threads with syscalls

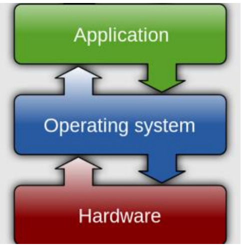
- Alternative: multiplex several streams of execution (at user level) on top of a single OS thread
  - E.g., Java, Go, … (and many many user-level threads libraries before it)



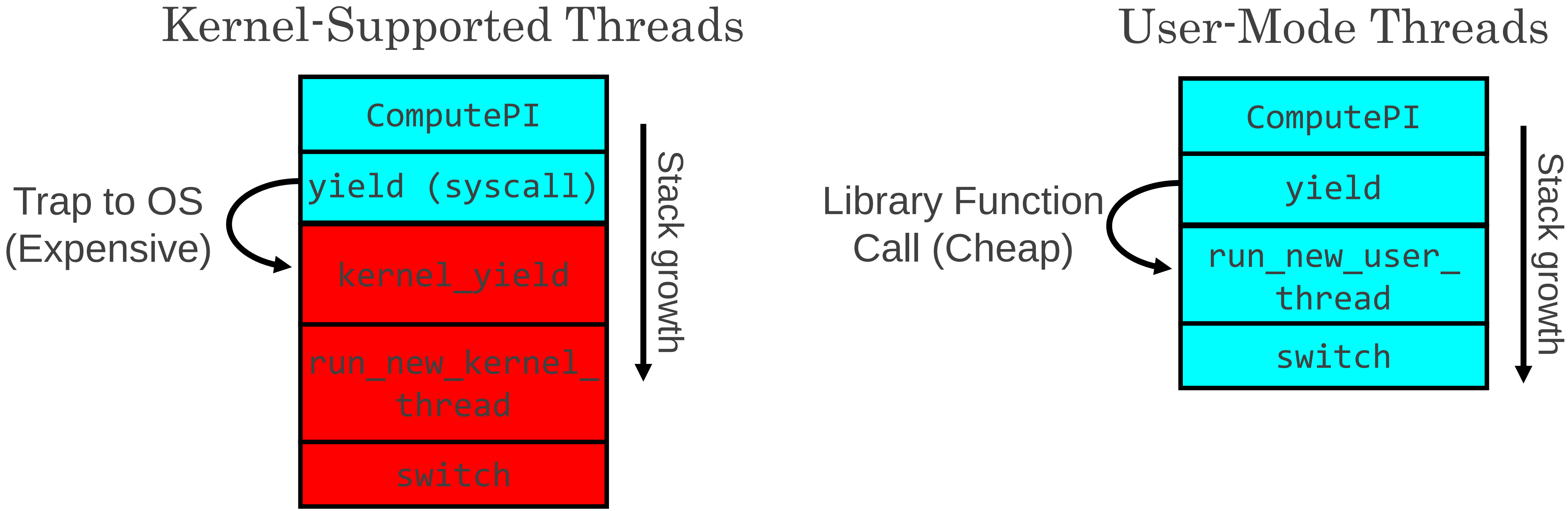
User-Mode Threads

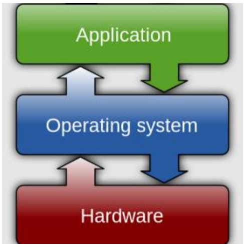
- User program contains its own scheduler
- Several user threads per kernel thread
- User threads may be scheduled non-preemptively
    - Only switch on yield
- Context switches cheaper
    - Copy registers and jump (switch in userspace)





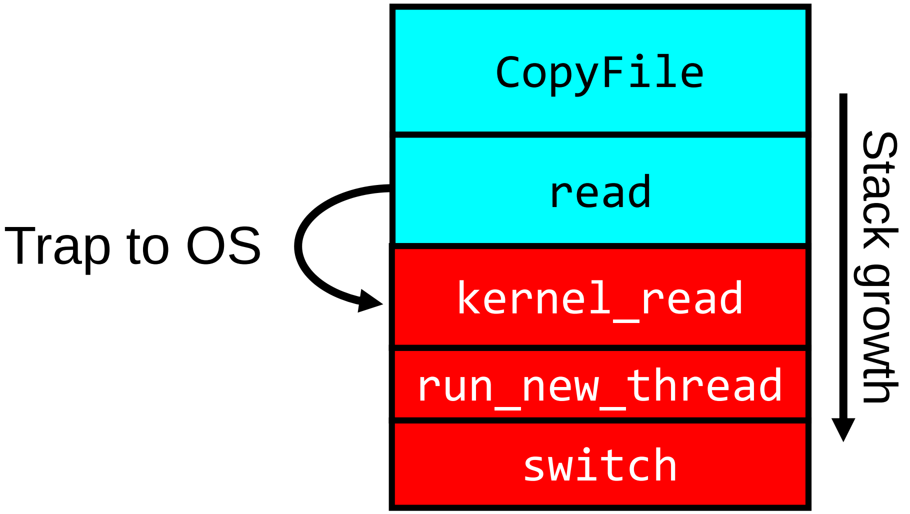
Thread Yield



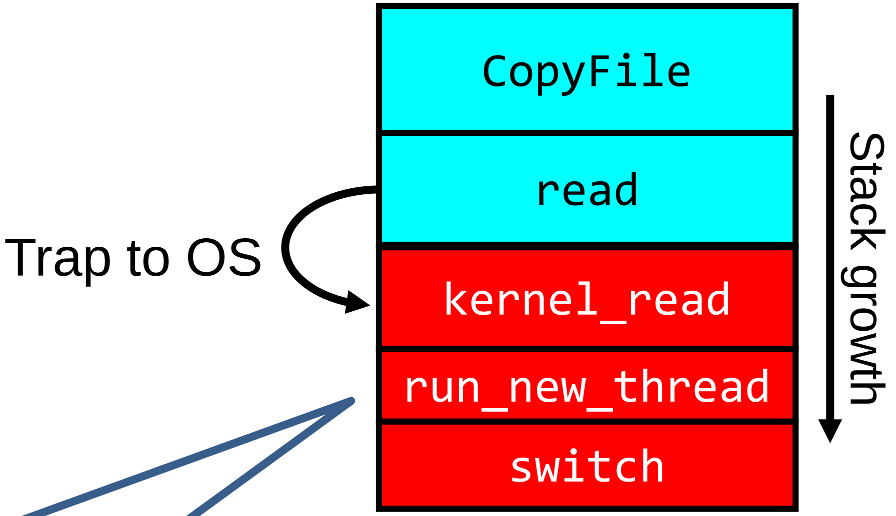


Thread I/O

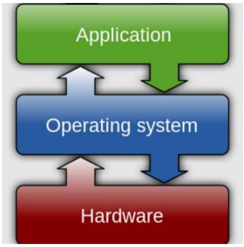
Kernel-Supported Threads



User-Mode Threads

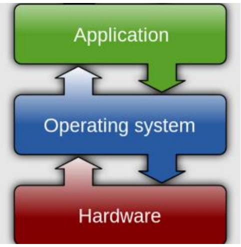


- Selects a new *kernel thread* to run
- Bypassing user-level scheduler



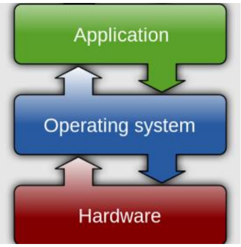
User-Mode Threads: Problems

- One user-level thread blocks on I/O: they all do
  - Kernel cannot adjust scheduling among threads it doesn't know about
- Multiple Cores?
- Can't completely avoid blocking (syscalls, page fault)
- One Solution: Scheduler Activations
  - Have kernel inform user-level scheduler when a thread blocks
  - Evolving the contract between OS and application
- Alternative Solution: Language Support?
  - Make the scheduler aware of the blocking operation



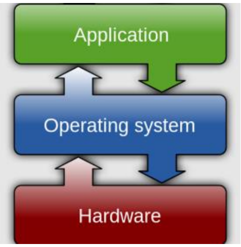
Go Goroutines

- Goroutines are lightweight, user-level threads
  - Scheduling not preemptive (relies on goroutines to yield)
  - Yield statements inserted by compiler
- Advantages relative to regular threads (e.g., pthreads)
  - More lightweight
  - Faster context-switch time
- Disadvantages
  - Less sophisticated scheduling at the user-level
  - OS is not aware of user-level threads



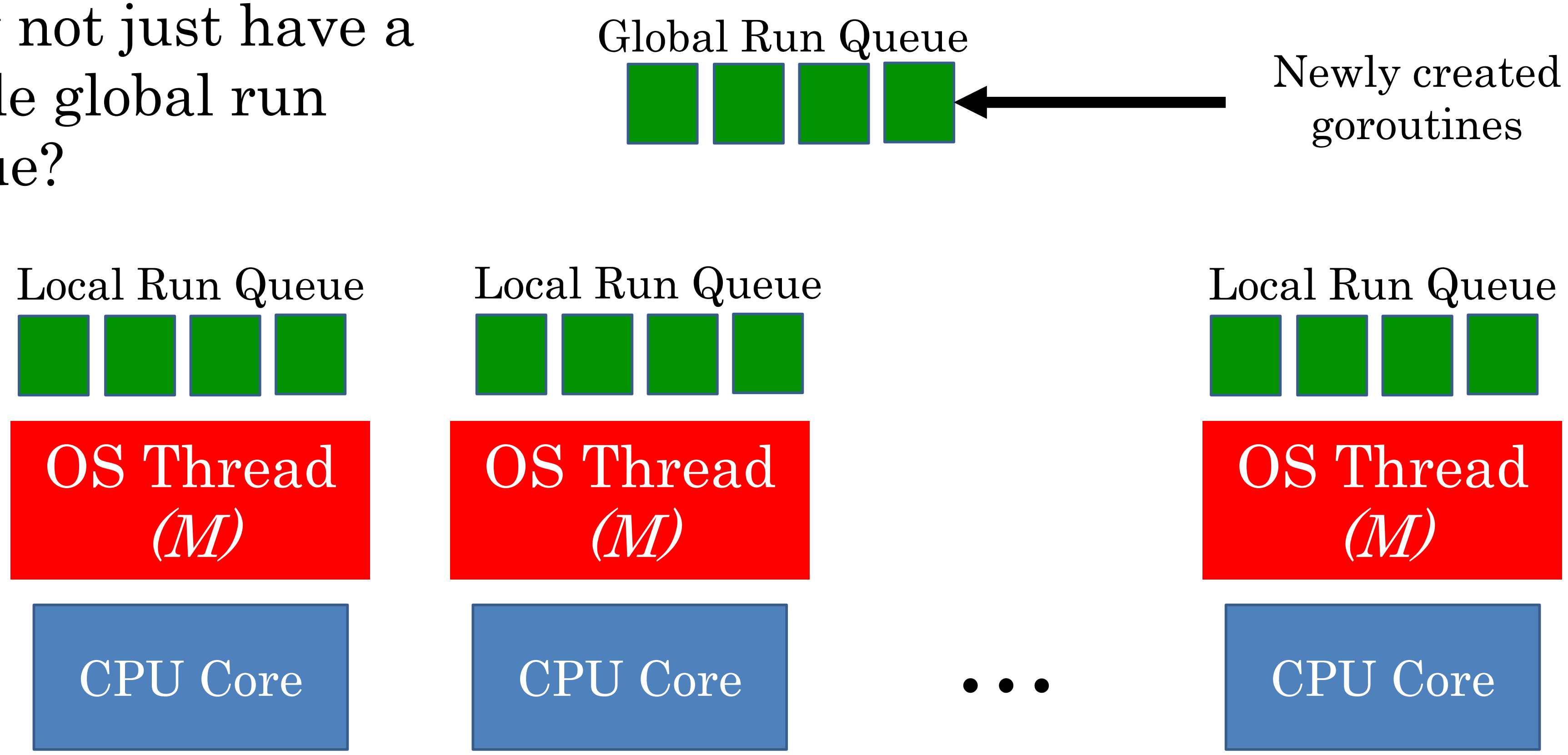
Go User-Level Scheduler

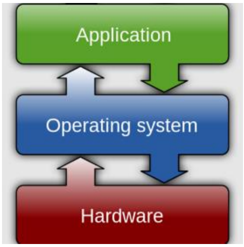
- Why this approach?
- 1 OS (kernel-supported) thread per CPU core: allows go program to achieve parallelism not just concurrency
  - Fewer OS threads? Not utilizing all CPUs
  - More OS threads? No additional benefit
    - We'll see one exception to this involving syscalls
- Keep goroutine on same OS thread: affinity, nice for caching and performance



Go User-Level Thread Scheduler

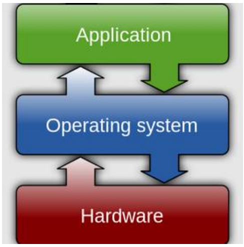
- Why not just have a single global run queue?



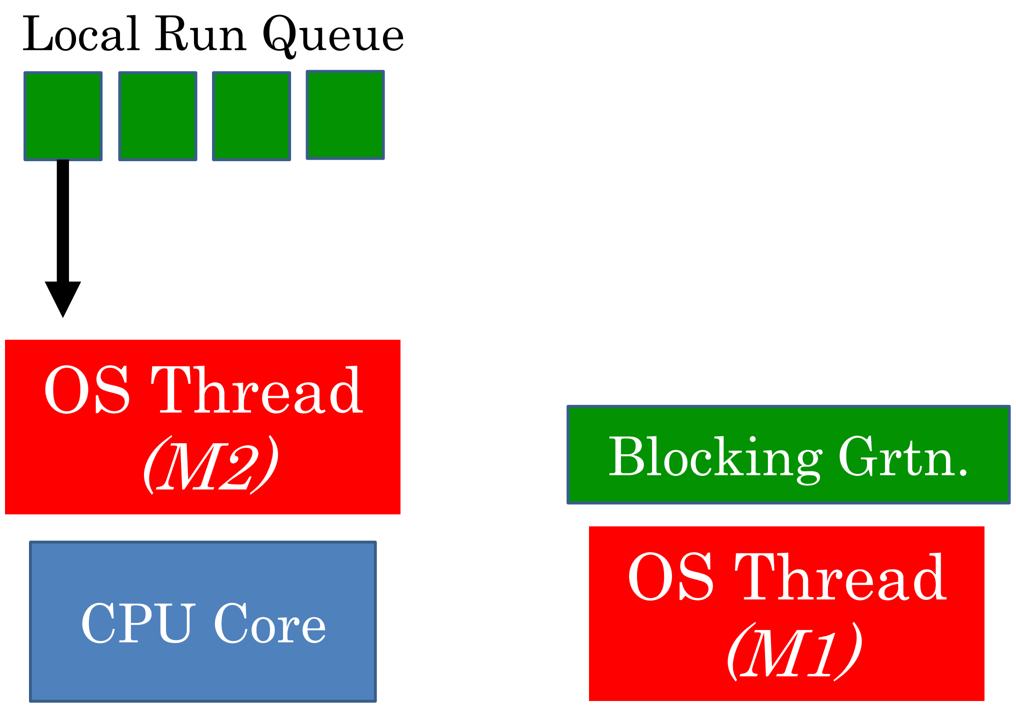


Dealing with Blocking Syscalls

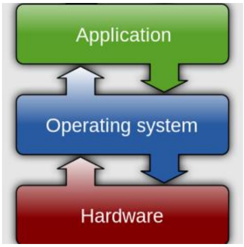
- What if a goroutine wants to make a blocking syscall?
  - Example: File I/O



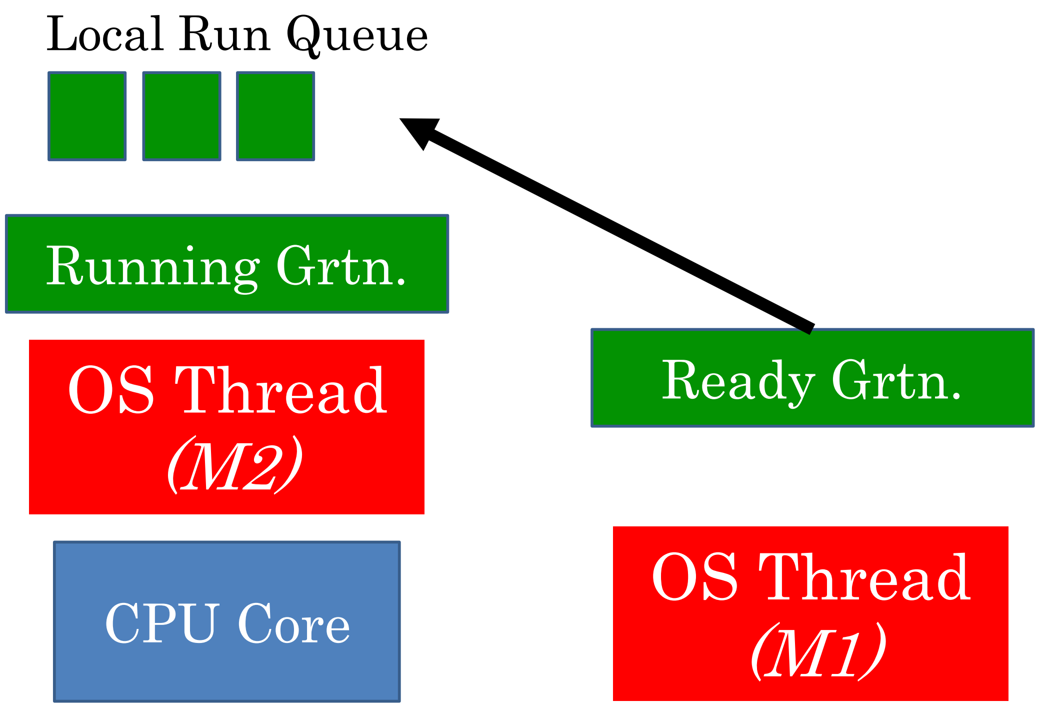
Dealing with Blocking Syscalls



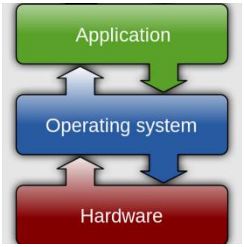
- What if a goroutine wants to make a blocking syscall?
  - Example: File I/O
- While syscall is blocking, allocate new OS thread (M2)
  - M1 is blocked by kernel, M2 lets us continue using CPU

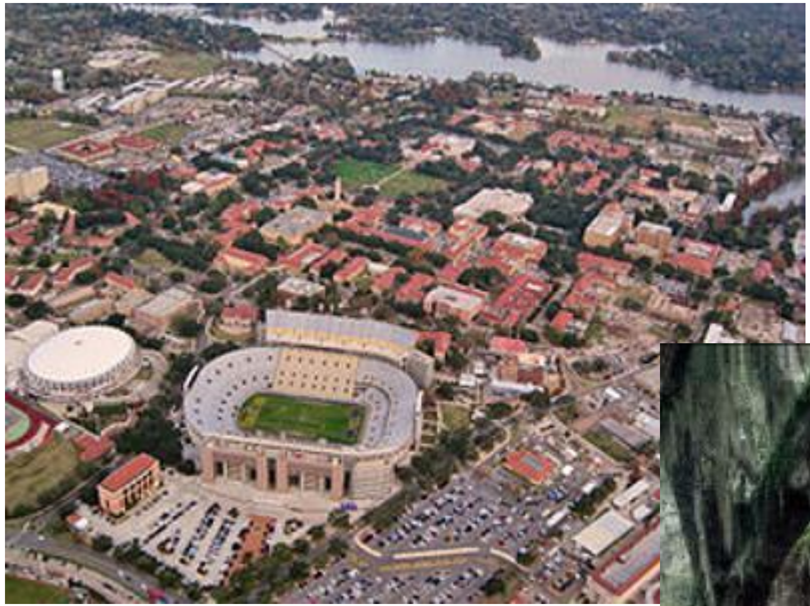


Dealing with Blocking Syscalls



- Syscall completes: Put invoking goroutine back on queue
- Keep M1 around in a spare pool
- Swap it with M2 upon next syscall, no need to pay thread creation cost





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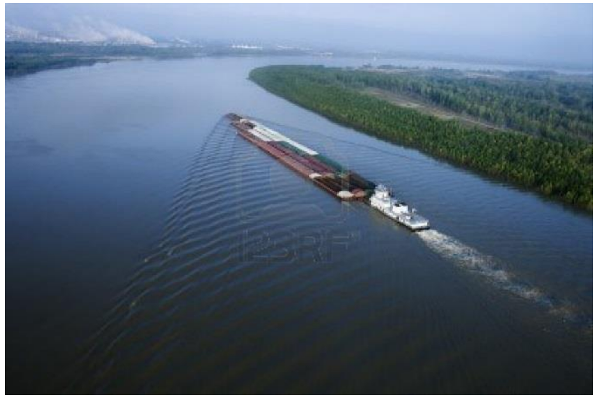

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