CS636: Shared Memory Synchronization

Swarnendu Biswas

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CSE, IIT Kanpur

Content influenced by many excellent references, see References slide for acknowledgements.

What is the desired property?

```
class Set {
  final Vector elems = new Vector();

  void add(Object x) {
    if (!elems.contains(x)) {
      elems.add(x);
    }
  }

}

class Vector {
  synchronized void add(Object o) { ... }
  synchronized boolean contains(Object o) { ... }
}
```

What is the desired property?

```
Q.insert(elem):
  atomic {
    while (Q.full()) {}
    // Add elem to the Q
  }
```

```
Q.remove():
  atomic {
    while (Q.empty()) {}
    // Return data from Q
  }
```

Implementing Synchronization Patterns

- Condition synchronization

```
while ¬ condition
  // do nothing (spin)
```

- Mutual exclusion

```
lock:bool := false
```

```
Lock.acquire():
  while TAS(&lock)
    // spin
```

```
Lock.release():
  lock := false
```

Locks (Mutual Exclusion)

```
public interface Lock {
  public void lock();
  public void unlock();
}

public class LockImpl
implements Lock {
  …
  …
}
```

```
Lock mtx = new LockImpl(…);
…
mtx.lock();
try {
  … // body
} finally {
  mtx.unlock();
}
```

Desired Synchronization Properties

- Mutual exclusion or safety

Critical sections on the same lock from different threads do not **overlap**

- Livelock freedom

If a lock is available, then **some** thread should be able to acquire it within bounded steps.

Desired Synchronization Properties

- Deadlock freedom

If some thread attempts to acquire the lock, then **some** thread should be able to acquire the lock

- Starvation freedom

- Every thread that acquires a lock **eventually** releases it
- A lock acquire request must eventually succeed within **bounded** steps

Classic Mutual Exclusion Algorithms

Peterson's Algorithm

```
class PetersonLock {

  static volatile boolean[] flag =
new boolean[2];
  static volatile int victim;

  public void unlock() {
    int i = ThreadID.get();
    flag[i] = false;
  }
```

```
  public void lock() {
    int i = ThreadID.get();
    int j = 1-i;
    flag[i] = true;
    victim = i;
    while (flag[j] && victim == i) {}
  }

}
```

Peterson’s Algorithm

```
class PetersonLock {

  static volatile
new boolean[2];

  static v

  public void u
    int i = ThreadID.get();
    flag[i] = false;
  }
```

```
 public void lock() {
   int i = ThreadID.get();
   int j = 1-i;

                 victim == i) {}

}
```

Is this algorithm correct under sequential consistency?

What could go wrong?

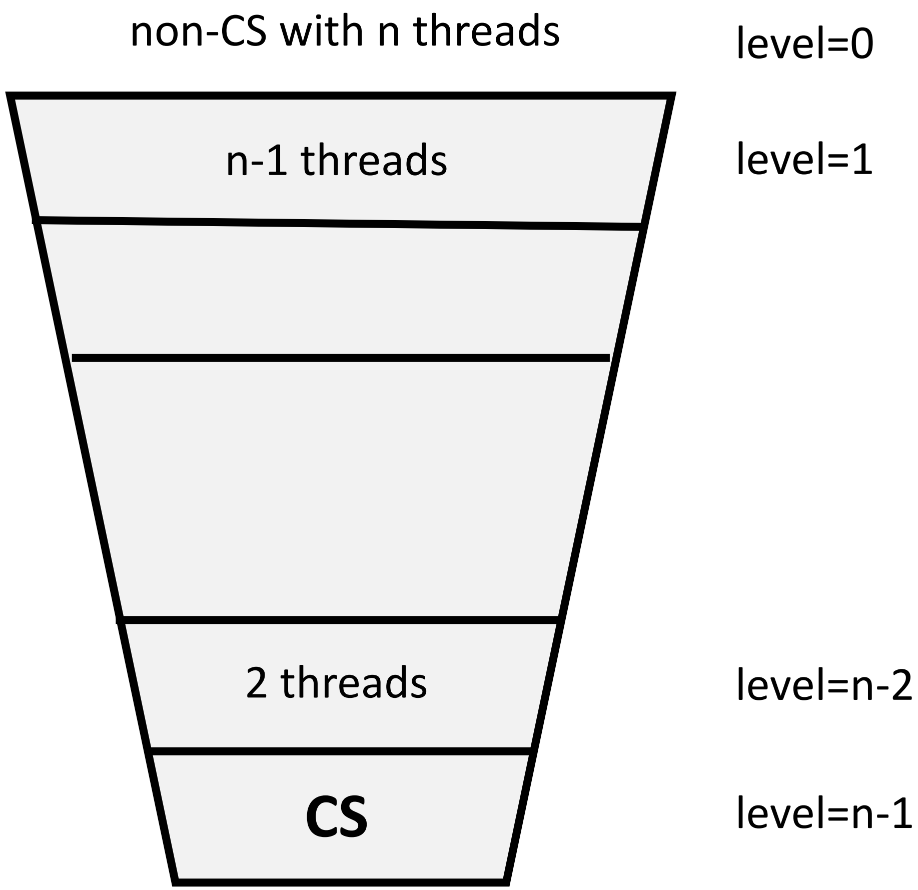
```
class TwoThreadLockFlags {

  static volatile boolean[] flag = new
boolean[2];

  public void lock() {
    int i = ThreadID.get();
    flag[i] = true;
    while (flag[j]) {} // wait
  }

  public void unlock() {
    int i = ThreadID.get();
    flag[i] = false;
  }

}
```

What could go wrong?

```
class TwoThreadLockVolatile {

  static volatile int victim;

  public void lock() {
    int i = ThreadID.get();
    victim = i; // wait for the other
    while (victim == i) {}
  }

  public void unlock() {
  }

}
```

Filter Algorithm

- There are n-1 waiting rooms called “levels”
- One thread gets blocked at each level if many threads try to enter



Filter Lock

```
class FilterLock {

  int[] level;
  volatile int[] victim;

  public FilterLock() {
    level = new int[n];
    victim = new int[n];
    for (int i = 0; i < n; i++) {
      level[i] = 0;
    }
  }
```

```
public void unlock() {
  int me = ThreadID.get();
  level[me]= 0;
}
```

Filter Lock

```
public void lock() {
  int me = ThreadID.get();
  for (int i = 1; i < n; i++) {
    level[me] = i; // visit level i
    victim[i] = me; // Thread me is a good guy!
    // spin while conflict exits
    while ((∃k != me) level[k] >= i && victim[i] == me) {
    }
  }
}

}
```

Fairness

- Starvation freedom is good, but maybe threads shouldn't wait too much…

- For example, it would be great if we could order threads by the order in which they performed the first step of the `lock()` method

Bounded Waiting

- Divide lock() method into two parts
  - Doorway interval (D_A) – finishes in finite steps
  - Waiting interval (W_A) – may take unbounded steps

r-Bounded Waiting

For threads A and B: if $D_A^k \rightarrow D_B^j$, then $CS_A^k \rightarrow CS_B^{j+r}$

Lamport’s Bakery Algorithm

```
class Bakery implements Lock {

  boolean[] flag;
  Label[] label;

 public void unlock() {
    flag[ThreadID.get()] = false;
  }
```

```
public Bakery(int n) {
   flag = new boolean[n];
   label = new Label[n];
   for (int i = 0; i<n; i++) {
     flag[i] = false;
     label[i] = 0;
   }
 }
```

Lamport’s Bakery Algorithm

(label[i], i) << (label[j], j)) iff label[i] < label[j] or label[i] = label[j] and $i < j$

```
  public void lock() {
    int i = ThreadID.get();
    flag[i] = true;
    label[i] = max(label[0], …, label[n-1]) + 1;
    while ((∃k != i) flag[k] && (label[k], k) << (label[i],i)) {}
  }

}
```

Lamport’s Fast Lock

- Programs with highly contended locks are likely to not scale
- **Insight:** **Ideally** spin locks should be free of contention

- Idea
  - Two lock fields x and y
  - Acquire: Thread t writes its id to x and y and checks for intervening writes

Lamport's Fast Lock

```
class LFL implements Lock {
  private int x, y;
  boolean[] trying;

  LFL() {
    y = ⊥;
    for (int i = 0; i<n; i++) {
      trying[i] = false;
    }
  }
```

```
public void unlock() {
  y = ⊥;
  trying[ThreadID.get()] = false;
}
```

Lamport's Fast Lock

```
public void lock() {
  int self = ThreadID.get();
  start:
    trying[self] = true;
    x = self;
    if (y != ⊥) {
      trying[self] = false;
      while (y != ⊥) {} // spin
      goto start;
    }
    y = self;
    if (x != self) {
      trying[self] = false;
      for (i ∈ T) {
        while (trying[i] == true) {
          // spin
        }
      }
      if (y != self) {
        while (y != ⊥) {} // spin
        goto start;
      }
    }
}}
```

Evaluation Lock Performance

- Lock acquisition latency
- Space overhead
- Fairness
- Bus traffic

Atomic Instructions in Hardware

Hardware Locks

- Locks can be completely supported by hardware
  - Not popular on bus-based machines
- Ideas:
  - Have a set of lock lines on the bus, processor wanting the lock asserts the line, others wait, priority circuit used for arbitrating
  - Special lock registers, processors wanting the lock acquired ownership of the registers
- What could be some problems?

Common Atomic (RMW) Primitives

test_and_set [x86, SPARC]

```
bool TAS(bool* loc):
  atomic {
    tmp := *loc;
    *loc := true;
    return tmp;
  }
```

swap [x86, SPARC]

```
word Swap(word* a, word b):
  atomic {
    tmp := *a;
    *a := b;
    return tmp;
  }
```

fetch_and_inc [uncommon]

```
int FAI(int* loc):
  atomic {
    tmp := *loc;
    *loc := tmp+1;
    return tmp;
  }
```

fetch_and_add [uncommon]

```
int FAA(int* loc, int n):
  atomic {
    tmp := *loc;
    *loc := tmp+n;
    return tmp;
  }
```

Common Atomic (RMW) Instructions

compare_and_swap [x86, IA-64, SPARC]

```
bool CAS(word* loc, world old, word new):
  atomic {
    res := (*loc == old);
    if (res)
      *loc := new;
    return res;
  }
```

Common Atomic (RMW) Instructions

compare_and_swap [x86, IA-64, SPARC]

```
bool CAS(word* loc, world old, word new):
  atomic {
    res := (*loc == old);
    if (res)
      *loc := new;
    return res;
  }
```

How can you implement fetch_and_func() with CAS?

Common Atomic (RMW) Instructions

load_linked/store_conditional [POWER, MIPS, ARM]

```
word LL(word* a):
  atomic {
    remember a;
    return *a;
  }

bool SC(word* a, word w):
  atomic {
    res := (a is remembered, and has not been evicted since LL)
    if (res)
      *a = w;
    return res;
  }
```

Common Atomic (RMW) Instructions

load_linked/store_conditional [POWER, MIPS, ARM]

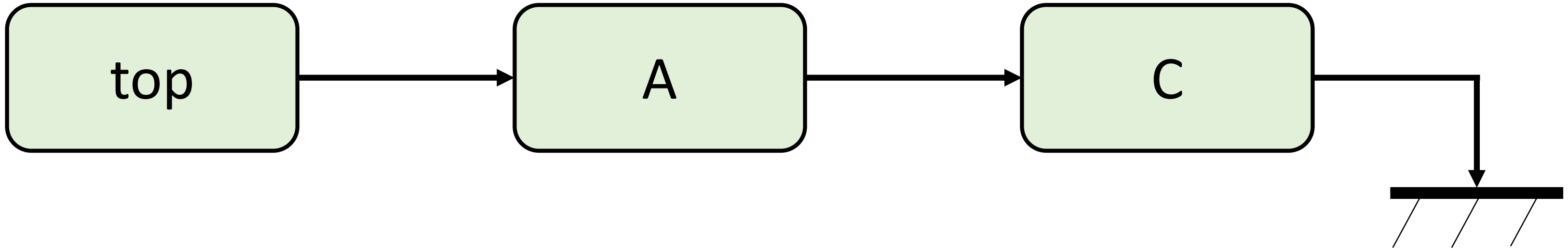
```
word LL(word* a):
  atomic {
    remember a;
    return *a;
  }

bool SC(word* a
  atomic {
    res := (                          ince LL)
    if (res)
      *a = w;
    return res;
  }
```

How can you implement fetch_and_func() with LL/SC?

ABA Problem

```
void push(node** top, node* new):
  node* old
  repeat
    old := *top
    new->next := old
  until CAS(top, old, new)
```

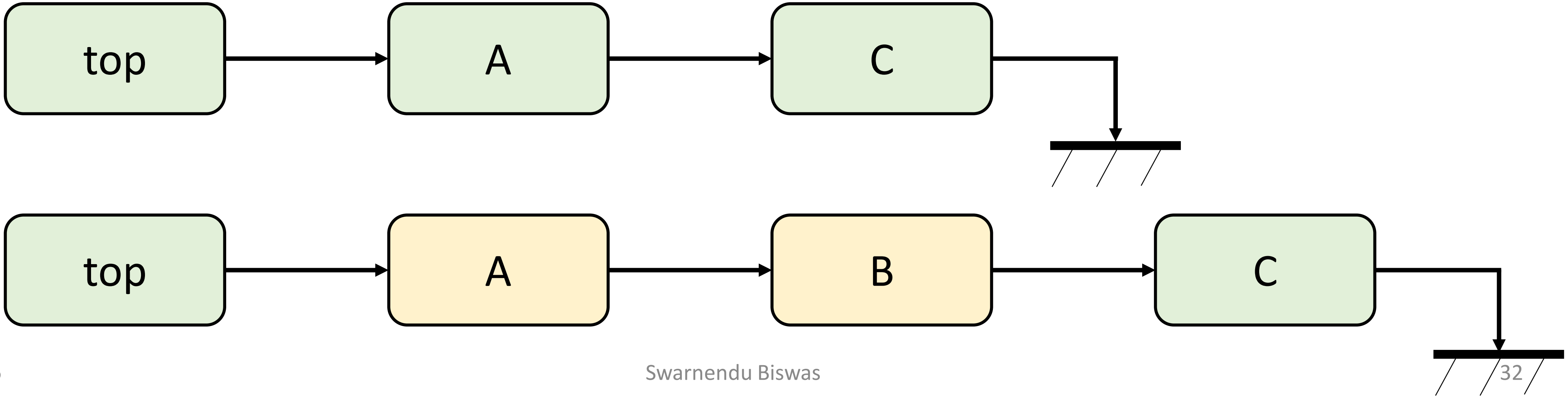
```
node* pop(node** top):
  node* old, new
  repeat
    old := *top
    if old = null return null
    new := old->next
  until CAS(top, old, new)
  return old
```



ABA Problem

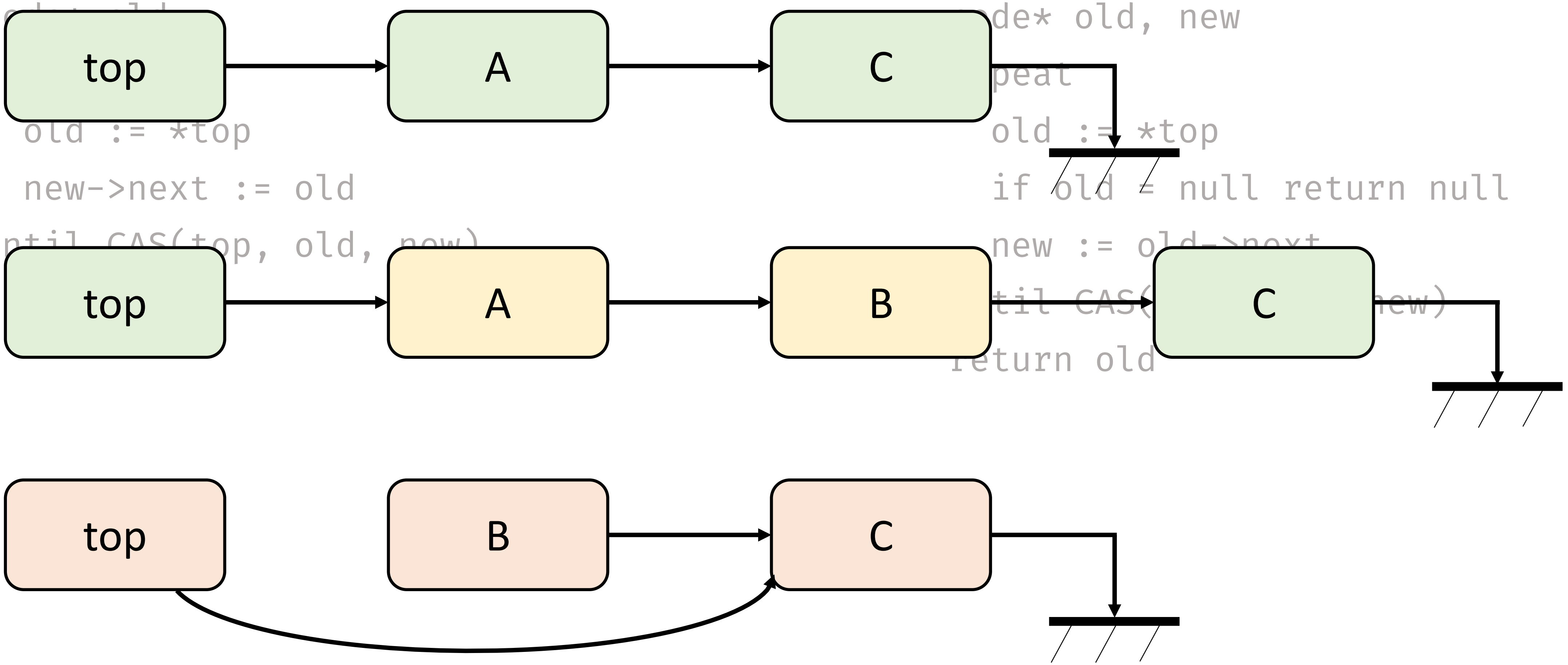
```
void push(node** top, node* new):
  node* old
  repeat
    old := *top
    new->next := old
  until CAS(top, old, new)
```

```
node* pop(node** top):
  node* old, new
  repeat
    old := *top
    if old = null return null
    new := old->next
  until CAS(top, old, new)
  return old
```



ABA Problem

```
void push(node** top, node* new):          node* pop(node** top):
```



Common Atomic (RMW) Instructions

compare_and_swap

- Cannot detect ABA

load_linked/store_conditional

- Guaranteed to fail
- SC can experience spurious failures
  - E.g., Cache miss, branch misprediction

Common Atomic (RMW) Instructions

load_linked/store_conditional [POWER, MIPS, ARM]

```
word LL(word* a):
  atomic {
    remember a;
    return *a
  }

bool SC
  atomic
    res                                    een evicted since LL)
    if (res)
      *a = w;
    return res;
  }
```

How can you reduce spurious failures in your fetch_and_func() implementation with LL/SC?

Centralized Mutual Exclusion Algorithms

Test-And-Set

- Atomically tests and sets a word
  - For example, swaps one for zero and returns the old value
- `java.util.concurrent.AtomicBoolean::getAndSet(bool val)`
- Bus traffic?
- Fairness?

```
bool TAS(bool* loc) {
  bool res;
  atomic {
    res = *loc;
    *loc = true;
  }
  return res;
}
```

Spin Lock with TAS

```
class SpinLock {
  bool loc = false;

  public void lock() {
    while (TAS(&loc)) {
      // spin
    }
  }

  public void unlock() {
    loc = false;
  }

}
```

Test-And-Test-And-Set

- Keep reading the memory location till the location **appears** unlocked
  - Reduces bus traffic – why?

```
do {
  while (TATAS_GET(loc)) {
  }
} while (TAS(loc));
```

Exponential Backoff

Larger number of unsuccessful retries
→ Higher the contention
→ Longer backoff
- Possibly double each time till a given maximum

Spin Lock with TAS and Backoff

```
class SpinLock {
  bool loc = false;
  const in MIN = …;
  cost int MUL = …;
  const int MAX = …;

  public void unlock() {
    loc = false;
  }
```

```
public void lock() {
   int backoff = MIN;
   while (TAS(&loc)) {
     pause(backoff);
     backoff = min(backoff * MUL,
                   MAX);
   }
  }
}
```

Challenges with Exponential Backoff

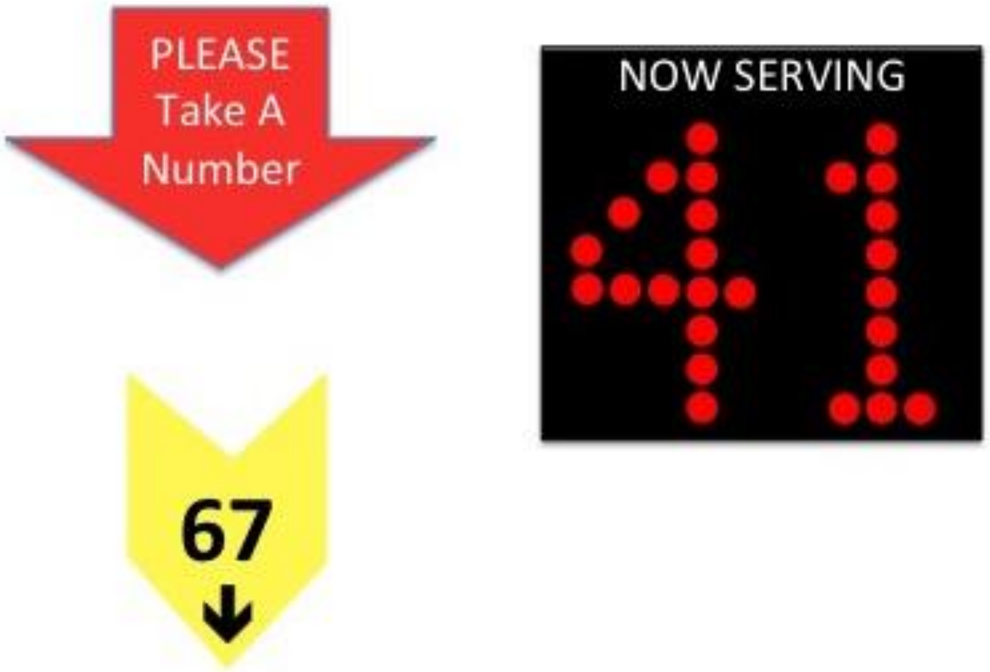
Larger number of unsuccessful retries
→ Higher the contention
→ Longer backoff

What can be some problems with this?

Fairness with TAS and TATAS Locks

Ticket Lock

- Grants access to threads based on FCFS
- Uses fetch_and_inc()



Ticket Lock

```
class TicketLock implements Lock
{

  int next_ticket = 0;
  int now_serving = 0;

  public void unlock() {
    now_serving++;
  }

  public void lock() {
    int my_ticket = FAI(&next_ticket);
    while (now_serving != my_ticket) {}
  }

}
```

Ticket Lock

```
class TicketLock implements Lock
{

  int next_ticket = 0;
  int now_serving = 0;

  public void unlock() {
    now_serving++;
  }

  public void lock() {
    int my_ticket = FAI(&next_ticket);
    while (now_serving != my_ticket) {}
  }

}
```

What are some disadvantages of Ticket locks?

Scalable Spin Locks

Queued Locks

- Key idea
  - Instead of contending on a single "`now_serving`" variable, make threads wait in a queue (i.e., FCFS).
  - Each thread knows its order in the queue.

Implementations

- Implement a queue using arrays
  - Statically or dynamically allocated depending on the number of threads
- Each thread spins on its **own lock** (i.e., array element), and knows the successor information

Queued Lock

```
public class ArrayLock implements
Lock {
  AtomicInteger tail;
  boolean[] flag;
  ThreadLocal<Integer> mySlot = …;

  public ArrayLock(int size) {
    tail = new AtomicInteger(0);
    flag = new boolean[size];
    flag[0] = true;
  }
```

```
  public void lock() {
    int slot = FAI(tail);
    mySlot.set(slot);
    while (!flag[slot]) {}
  }

  public void unlock() {
    int slot = mySlot.get();
    flag[slot] = false;
    flag[slot+1] = true;
  }
}
```

Queued Locks

- Key idea
  - Instead of contending on a single "`now_serving`" variable, make threads wait in a queue.
  - Each thread kn

What could be a few disadvantages of array-based Queue locks?

Implementations
- Implement a queue usin rrays
  - Statically or dynamically allocated depending on the number of threads
- Each thread spins on its own lock (i.e., array element), and knows the successor information

Queued Locks using Arrays

```
public class ArrayLock implements
Lock {
  AtomicInteger tail;
  boolean[] flag;
  ThreadLocal<Integer> mySlot = …;

  public ArrayLock(int size) {
    tail = new AtomicInteger(0);
    flag = new boolean[size];
    flag[0] = true;
  }

  public void lock() {
    int slot = FAI(tail);
    mySlot.set(slot);
    while (!flag[slot]) {}
  }

  public void unlock() {
    int slot = mySlot.get();
    flag[slot] = false;
    flag[slot+1] = true;
  }
}
```

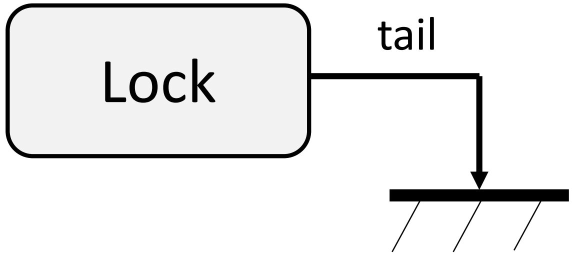
MCS Queue Lock

- Proposed by Mellor-Crumney and Scott [1991]
- Uses linked lists instead of arrays
- **Space required to support n threads and k locks: O(n+k)**
- **State-of-art scalable FIFO locks**

MCS Queue Lock

```
class QNode {
  QNode next;
  bool waiting;
}
public class MCSLock implements Lock {
  Node tail = null;
  ThreadLocal<QNode> myNode = …;

  public void lock() {
    QNode node = myNode.get();
    QNode prev = swap(tail, node);
    if (prev != null)
      node.waiting = true;
      prev.next = node;
      while (node.waiting) {}
  }

  public void unlock() {
    QNode node = myNode.get();
    QNode succ = node.next;
    if (succ == null)
      if (CAS(tail, node, null))
        return;
      do {
        succ = node.next;
      } while (succ == null);
    succ.waiting = false;
  }
}
```

MCS Lock Operations



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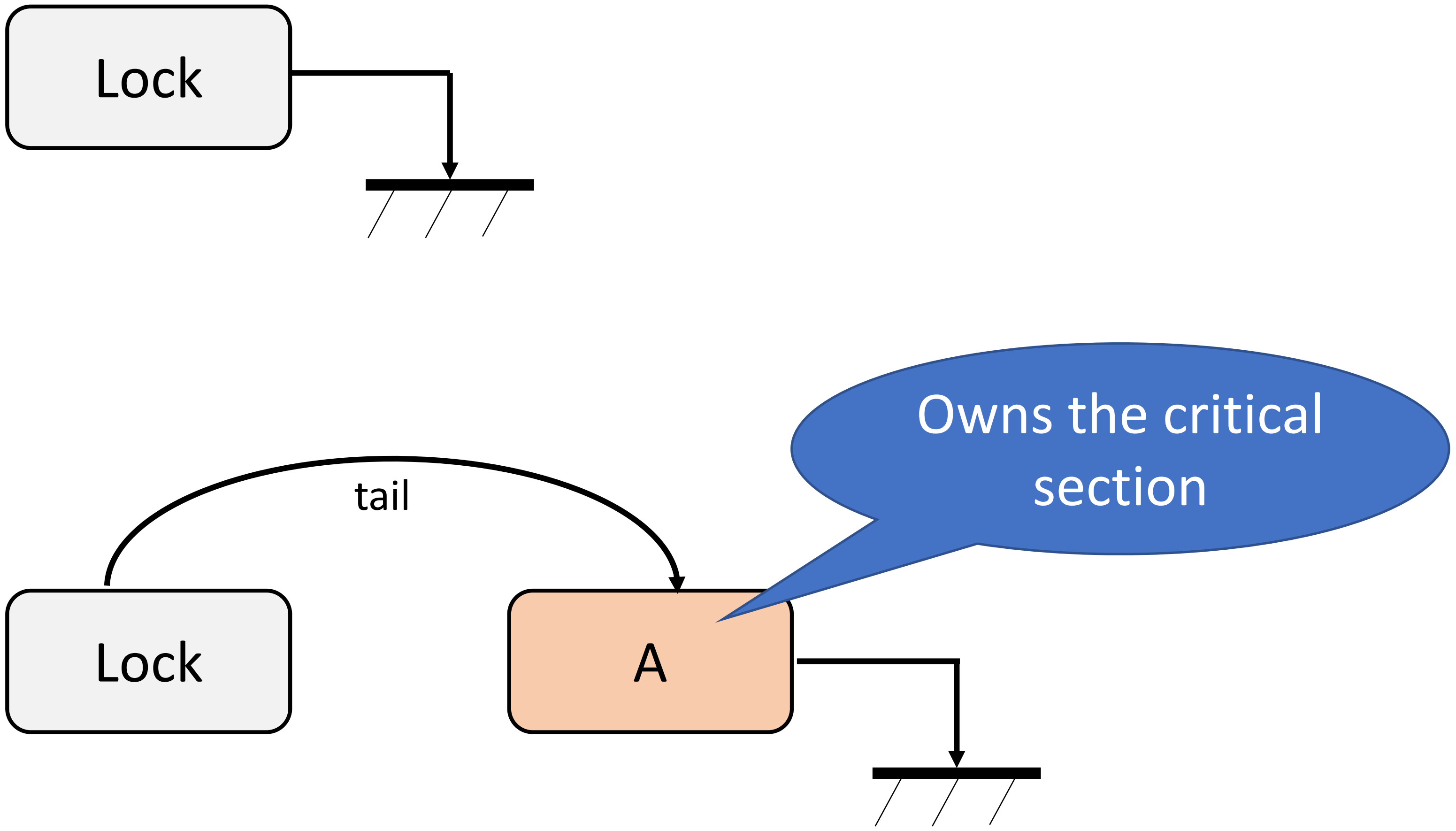

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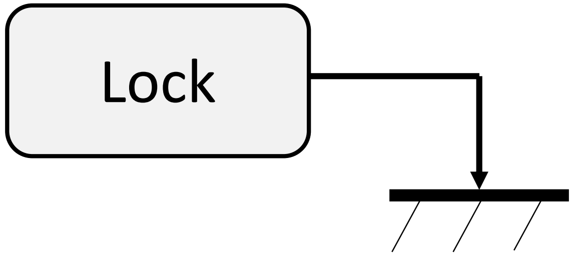

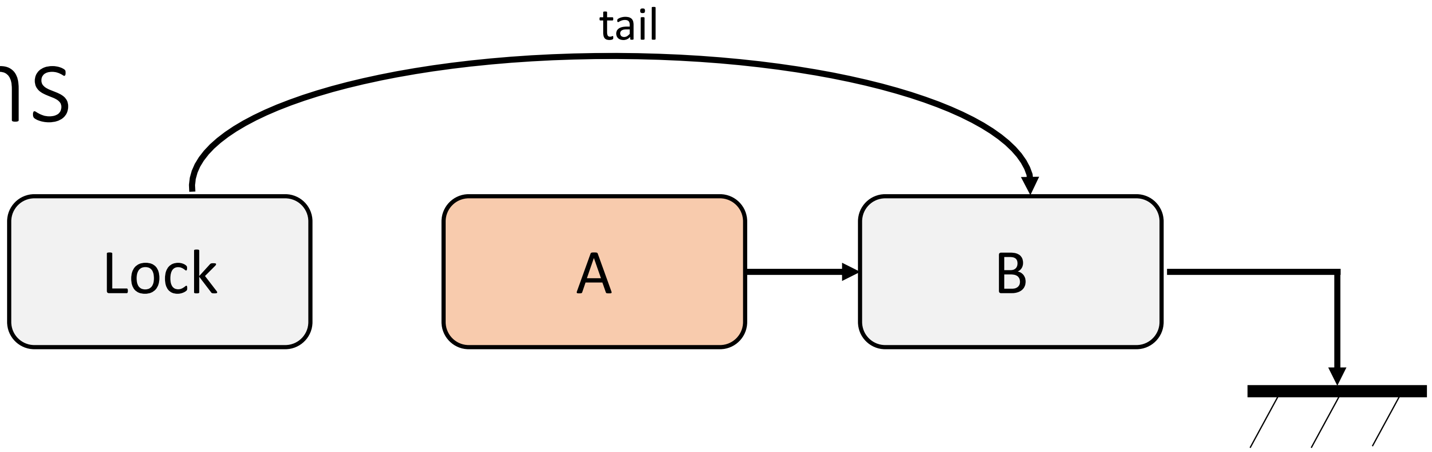

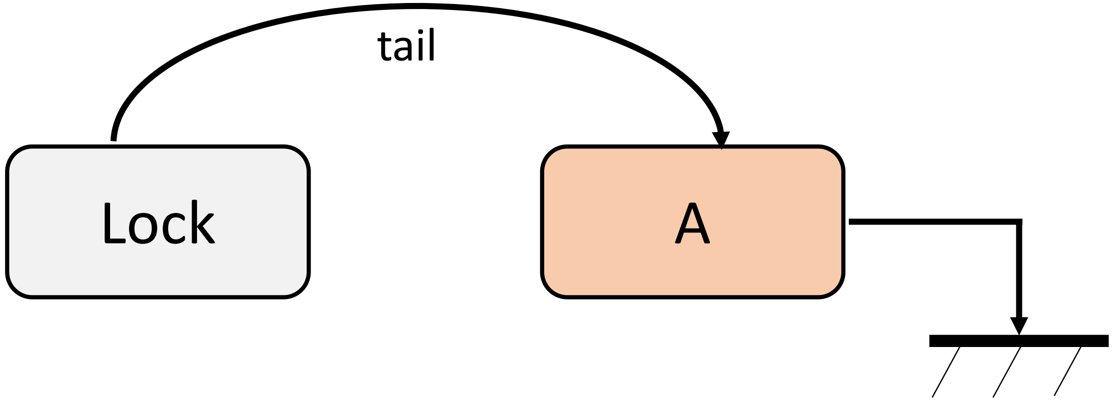

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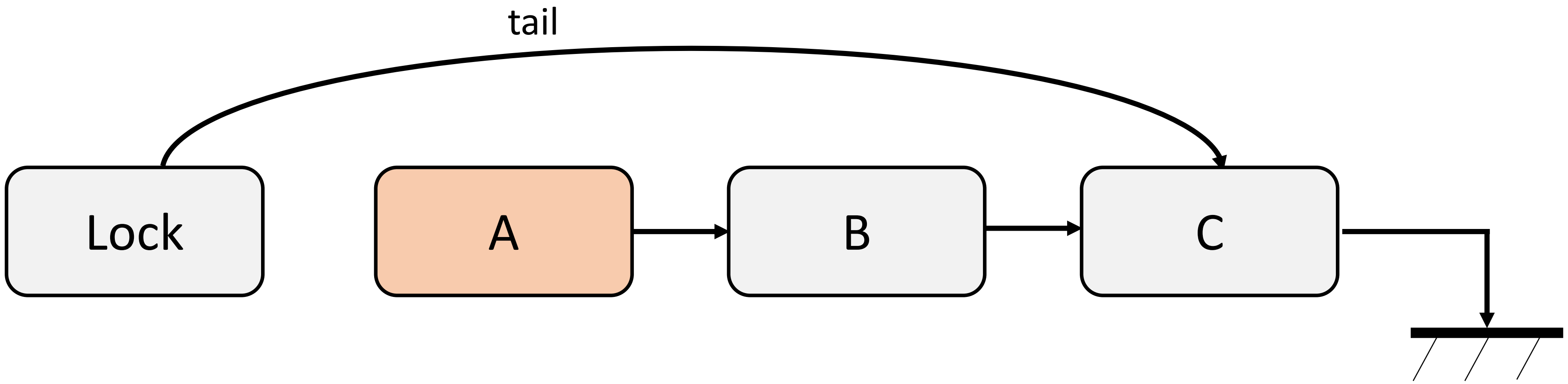
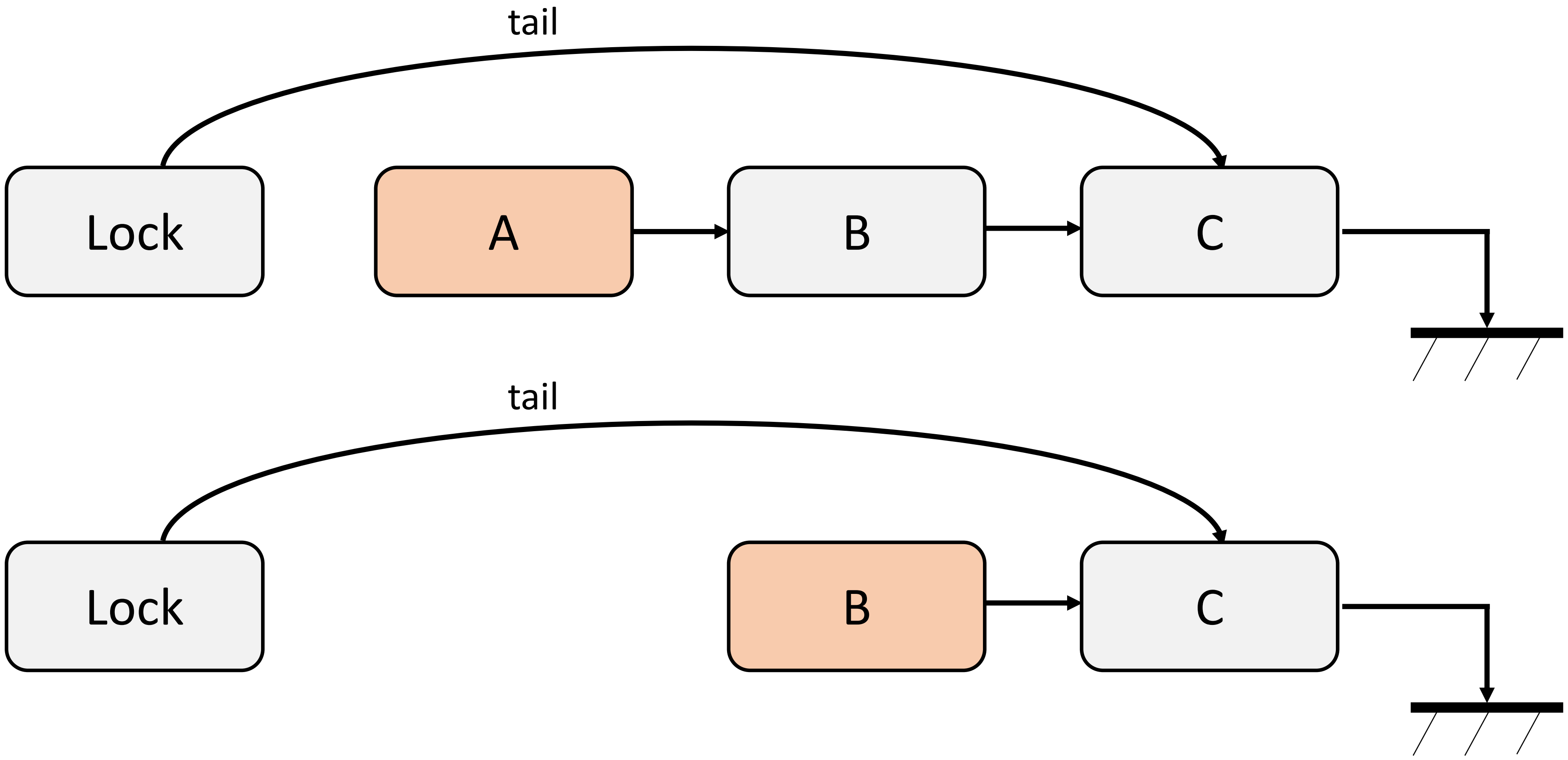


MCS Lock Operations



Which Spin Lock should I use?

- Limited use of load-store-only locks
- Limited contention (e.g., few threads)
  - TAS spin locks with exponential backoff
  - Ticket locks
- High contention
  - MCS lock

Miscellaneous Lock Optimizations

Reentrant Locks

- A lock that can be **re-acquired** by the owner thread
- Freed after an equal number of releases

```
public class ParentWidget {

  public synchronized void doWork() {
    …
  }
}
```

```
public class ChildWidget extends ParentWidget {

  public synchronized void doWork() {
    …
    super.doWork();
    …
  }
}
```

Lazy Initialization In Single-Threaded Context

```
class Foo {
  private Helper helper = null;
  public Helper getHelper() {
    if (helper == null) {
      helper = new Helper();
    }
    return helper;
  }
  …
}
```

Correct for single thread

Lazy initialization

http://www.cs.umd.edu/~pugh/java/memoryModel/DoubleCheckedLocking.html

Lazy Initialization In Multithreaded Context

```
class Foo {
  private Helper helper = null;
  public Helper getHelper() {
    if (helper == null) {
      helper = new Helper();
    }
    return helper;
  }
  …
}
```

```
class Foo {
  private Helper helper = null;
  public synchronized Helper getHelper() {
    if (helper == null) {
      helper = new Helper();
    }
    return helper;
  }
  …
}
```

http://www.cs.umd.edu/~pugh/java/memoryModel/DoubleCheckedLocking.html

Can we optimize the initialization pattern?

1. Check if helper is initialized. If yes, return.
2. If no, then obtain a lock.
3. Double check whether the helper has been initialized. If yes, return.
   - Perhaps concurrently initialized in between Steps 1 and 2.
4. Initialize helper, and return.

Broken Usage of Double Checked Locking

```
class Foo {
  private Helper helper = null;
  public Helper getHelper() {
    if (helper == null) {
      synchronized (this) {
        if (helper == null)
          helper = new Helper();
      }
    }
    return helper;
  }
  …
}
```

One Correct Use of Double Checked Locking

```
class Foo {
  private volatile Helper helper = null;
  public Helper getHelper() {
    if (helper == null) {
      synchronized (this) {
        if (helper == null)
          helper = new Helper();
      }
    }
    return helper;
  }
  …
}
```

Reader-Writer Locks

- Many objects are read concurrently
  - Updated only a few times
- Reader lock
  - No thread holds the write lock
- Writer lock
  - No thread holds the reader or writer locks

```
public interface RWLock {
  public void readerLock();
  public void readerUnlock();

  public void writerLock();
  public void writerUnlock();
}
```

Issues to Consider in Reader-Writer Locks

Design choices		
	Release preference order	Writer releases lock, both readers and writers are queued up
	Incoming readers	Writers waiting, and new readers are arriving
	Downgrading	Can a thread acquire a read lock without releasing the write lock?
	Upgrading	Can a read lock be **upgraded** to a write lock?

Reader-Writer Locks

- Reader or writer preference
  - Allows starvation of non-preferred threads

```
readerLock():
  acquire(rd)
  rdrs++
  if rdrs == 1:
    acquire(wr)
  release(rd)
```

```
readerUnlock():
  acquire(rd)
  rdrs--
  if rdrs == 0:
    release(wr)
  release(rd)

writerLock():
  acquire(wr)

writerUnlock():
  release(wr)
```

Reader-Writer Lock With Reader-Preference

```
class RWLock {
  int n = 0;
  const int WR_MASK = 1;
  const int RD_INC = 2;

  public void writerLock() {
    while (¬ CAS(&n, 0, WR_MASK)) {
    }
  }
}
```

```
public void writerUnlock() {
  FAA(&n, -WR_MASK);
}

public void readerLock() {
  FAA(&n, RD_INC);
  while ((n & WR_MASK) == 1) {
  }
}

public void readerUnlock() {
  FAA(&n, -RD_INC);
}
```

Asymmetric Locks

- Often objects are locked by at most one thread
- Biased locks
  - JVMs use biased locks, the acquire/release operations on the owner threads are cheaper
    - Usually biased to the first owner thread
  - Synchronize only when the lock is contended, need to take care of several subtle issues
  - `-XX:+UseBiasedLocking` in HotSpot JVM

https://blogs.oracle.com/dave/biased-locking-in-hotspot

Monitors

Using Locks to Access a Bounded Queue

- Suppose I have a **bounded** FIFO queue
- Many producer threads and one consumer thread access the queue

```
mutex.lock();
try {
  queue.enq(x);
} finally {
  mutex.unlock();
}
```

Using Locks to Access a Bounded Queue

- Suppose I have a **bounded** FIFO queue
- Many producer threads and one consumer thread access the queue

```
mutex.lock();
try {
  queue.enq(x);
} finally {
  mutex.unlock();
}
```

What could be some problems?

Monitors to the Rescue!

- Combination of methods, mutual exclusion locks and condition variables

```
public synchronized void enque() {
  queue.enq(x);
}
```

- Provides **mutual exclusion for methods**
- Provides the possibility to **wait for a condition (cooperation)**

Condition Variables in Monitors

- Have an associated queue
- Operations
  - **wait**
  - **notify** (signal)
  - **notifyAll** (broadcast)

Condition Variable Operations

wait var, mutex

- Make the thread wait until a condition *COND* is true
  - Releases the **monior’s mutex**
  - Moves the thread to var’s wait queue
  - Puts the thread to sleep
- **Steps 1-3 are atomic to prevent race conditions**
- When the thread wakes up, it is assumed to hold mutex

Condition Variable Operations

notify var

- Invoked by a thread to assert that *COND* is true
- Moves one or more threads from the wait queue to the ready queue

notifyAll var

- Moves all threads from wait queue to the ready queue

Signaling Policies

Signal and continue (SC)	Signaler thread holds the lock. Java implements SC only.
Signal and wait (SW)	Signaler thread needs to reacquire the lock, signaled thread can continue execution
Signal and urgent wait (SU)	Like SW, but signaler thread gets to go after the signaled thread
Signal and exit (SX)	Signaler exits, signaled thread can continue execution.

Using Monitors

- Have an associated queue
- Operations
  - **wait**
  - **notify** (signal)
  - **notifyAll** (broadcast)

```
acquire(mutex)
while (!COND) {
  wait(var, mutex)
}
…
/* CRITICAL SECTION */
…
notify(var)/notifyAll(var)
release(mutex)
```

Producer-Consumer with Monitors

```
Queue q;
Mutex mtx; // Has associated queue
CondVar empty, full;

producer:
  while true:
    data = new Data(…);
    acquire(mtx);
    while q.isFull():
      wait(full, mtx);
    q.enq(data);
    notify(empty);
    release(mtx);
```

```
consumer:
  while true:
    acquire(mtx)
    while q.isEmpty():
      wait(empty, mtx);
    data = q.deq();
    notify(full);
    release(mtx);
    …
    …
```

Contrast with Producer-Consumer with Spin Locks

```
Queue q;
Mutex mtx;

producer:
  while true:
    data = new Data(…);
    acquire(mtx);
    while q.isFull():
      release(mtx);
      …
      acquire(mtx);
    q.enq(data);
    release(mtx);
```

```
consumer:
  while true:
    acquire(mtx);
    while q.isEmpty():
      release(mtx);
      …
      acquire(mtx);
    data = q.deq();
    release(mtx);
    …
    …
```

Semaphore Implementation with Monitors

```
int numRes = N;
Mutex mtx;
CondVar zero;

P:
  acquire(mtx);
  while numRes == 0:
    wait(zero, mtx);
  assert numRes > 0
  numRes--;
  release(mtx);
```

```
V:
  acquire(mtx);
  numRes++;
  notify(zero);
  release(mtx);
```

Reader-Writer Locks with Reader-Preference

- Reader or writer preference
  - Allows starvation of non-preferred threads

```
readerLock():
  acquire(rd)
  rdrs++
  if rdrs == 1:
    acquire(wr)
  release(rd)
```

```
readerUnlock():
  acquire(rd)
  rdrs--
  if rdrs == 0:
    release(wr)
  release(rd)

writerLock():
  acquire(wr)

writerUnlock():
  release(wr)
```

Reader-Writer Locks

- Reader or writer preference
  - Allows starvation of non-preferred threads

How can we construct a Reader-Writer lock with writer-preference?

```
readerL
  acquire(rd)
  rdrs++
  if rdrs == 1:
    acquire(wr)
  release(rd)
```

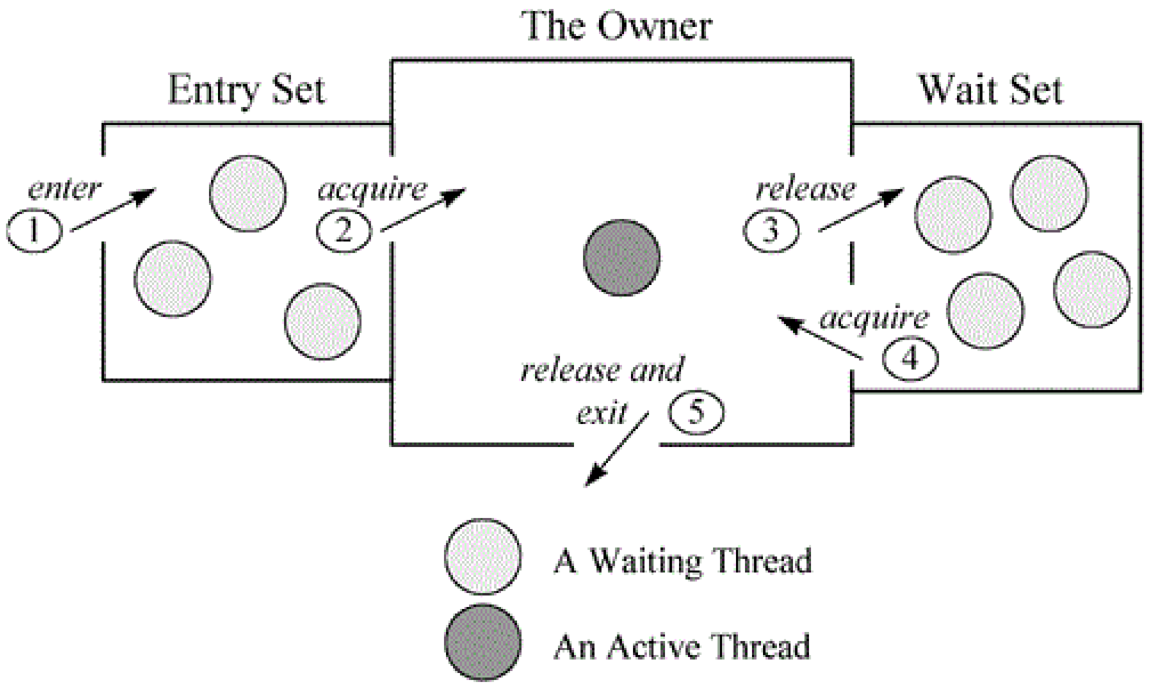
```
readerUnlock():
  acquire(rd)
```

```
writerLock():
  acquire(wr)

writerUnlock():
  release(wr)
```

Monitors in Java

- Java provides built-in support for monitors
    - **synchronized** blocks and methods
    - wait(), notify(), and notifyAll()
- Each object can be used as a monitor



https://www.artima.com/insidejvm/ed2/threadsynch.html

Bounded Buffer with Monitors in Java

```
import java.util.concurrent.locks.Condition;
import java.util.concurrent.locks.Lock;
import java.util.concurrent.locks.ReentrantLock;

public class BoundedBuffer {
  private final String[] buffer;
  private final int capacity; // Constant, length of buffer
  private int count; // Current size
  private final Lock lock = new ReentrantLock();
  private final Condition full = new Condition();
  private final Condition empty = new Condition();
```

Bounded Buffer with Monitors in Java

```
public void addToBuffer() … {
  lock.lock();
  try {
    while (count == capacity)
      full.await();
    …
    …
    empty.signal();
  } finally {
    lock.unlock();
  }
}
```

```
public void removeFromBuffer() … {
  lock.lock();
  try {
    while (count == 0)
      empty.await();
    …
    …
    full.signal();
  } finally {
    lock.unlock();
  }
 }
}
```

References

- Michael Scott. Shared Memory Synchronization. Morgan and Claypool Publishers.
- M. Herlihy and N. Shavit. The Art of Multiprocessor Programming. Morgan Kaufmann Publishers.
- B. Goetz et al. Java Concurrency in Practice. Pearson.