15-440
Distributed Systems
Recitation 8

Slides By: Hend Gedawy
& Previous TAs
Announcements

• **PS3** Due Today
• **P2** Due October 24
  • *(next Tuesday)*
Outline

• Project 2 Objectives Recap
• Dining Philosophers & Deadlocks
• Synchronization in Project 2
• Implementing Synchronization in Java
1. Devise and apply a synchronization algorithm that:
   - achieves correctness while sharing files
   - and ensures fairness to clients.

2. Devise and apply a replication algorithm that:
   - achieves load-balancing among storage servers
   - and ensures consistency of replicated files.
Project 2 Objectives: Reminder

1. Devise and apply a *synchronization algorithm* that:
   - achieves *correctness* while sharing files
   - and ensures *fairness* to clients.

2. Devise and apply a replication algorithm that:
   - achieves load-balancing among storage servers
   - and ensures consistency of replicated files.
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Dining Philosophers

One of the classic problems used to describe synchronization issues in accessing shared resources by multiple entities and illustrate techniques for solving them.
Dining Philosophers

- **5 Silent philosophers** (P1 - P5)
- Actions: **Thinking and Eating**
- **5 Forks** to share (F1 - F5)

- Each Pi needs a pair of forks
- When Pi is done eating, he is back to thinking and puts back his forks

**Goal:** come up with a scheme/protocol that helps the philosophers achieve their goal of eating and thinking without getting starved to death
Dining Philosophers

Step 1: think until the left fork is available; when it is, pick up;

Step 2: think until the right fork is available; when it is, pick up;

Step 3: when both fork are held, eat for some time;

Step 4: then, put the right fork down;

Step 5: then, put the left fork down;

Step 6: repeat from the beginning
Dining Philosophers

A concurrent system with a need for synchronization, should ensure

Correctness
Dining Philosophers

A concurrent system with a need for synchronization, should ensure

Correctness

No two philosophers should be using the same forks at the same time.
Dining Philosophers

A concurrent system with a need for synchronization, should ensure

**Correctness**

No two philosophers should be using the same forks at the same time.

**Efficiency**
Dining Philosophers

A concurrent system with a need for synchronization, should ensure

Correctness

No two philosophers should be using the same forks at the same time.

Efficiency

Philosophers do not wait too long to pick-up forks when they want to eat.
Dining Philosophers

A concurrent system with a need for synchronization, should ensure

Correctness

No two philosophers should be using the same forks at the same time.

Efficiency

Philosophers do not wait too long to pick-up forks when they want to eat.

Fairness
Dining Philosophers

A concurrent system with a need for synchronization, should ensure

**Correctness**
No two philosophers should be using the same forks at the same time.

**Efficiency**
Philosophers do not wait too long to pick-up forks when they want to eat.

**Fairness**
No philosopher should be unable to pick up forks forever and starve.
Pseudocode

```plaintext
while(true) {
    // Initially, thinking about life, universe, and everything
    think();
    // Take a break from thinking, hungry now
    pick_up_left_fork();
pick_up_right_fork();
eat();
    put_down_right_fork();
    put_down_left_fork();

    // Not hungry anymore. Back to thinking!
}
```

What’s wrong with this code
Dining Philosophers
A deadlock is a situation where the progress of a system is halted as each process is waiting to acquire a resource held by some other process.
Dining Philosophers
Dining Philosophers

A concurrent system with a need for synchronization, should ensure:

**Correctness**

No two philosophers should be using the same chopsticks at the same time.

**Efficiency**

Philosophers do not wait too long to pick-up chopsticks when they want to eat.

**Fairness**

No philosopher should be unable to pick up chopsticks forever and starve.

How do we fix this?
Dining Philosophers – Handling the Deadlock of Circular Waits

Initial Protocol

```java
Philosopher (Object firstForkToPick, Object secondForkToPick)

for (int i = 0; i < philosophers.length; i++) {
    Object leftFork = forks[i];
    Object rightFork = forks[(i + 1) % forks.length];
    philosophers[i] = new Philosopher(leftFork, rightFork);
    Thread t = new Thread(philosophers[i], "Philosopher " + (i + 1));
    t.start();
}
```
Dining Philosophers – Handling the Deadlock of Circular Waits

Breaking the Waiting Circle

```java
Philosopher (Object firstForkToPick, Object SecondForkToPick)

for (int i = 0; i < philosophers.length; i++) {
    Object leftFork = forks[i];
    Object rightFork = forks[(i + 1) % forks.length];
    if (i == philosophers.length - 1) {
        // The last philosopher picks up the right fork first
        philosophers[i] = new Philosopher(rightFork, leftFork);
    } else {
        philosophers[i] = new Philosopher(leftFork, rightFork);
    }

    Thread t = new Thread(philosophers[i], "Philosopher " + (i + 1));
    t.start();
}
```
Deadlocks-
Account Transfer Example

Sana -> Abdalla
`synchronized(from) {
  if (from.getbal() > val)
  from.post(-val);
}
```
synchronized(to)
```

Abdalla -> Sana
`synchronized(from) {
  if (from.getbal() > val)
  from.post(-val);
}
```
synchronized(to)
```

How to fix?

DEADLOCKED!!!!

Sana wants to transfer 10 riyals to Abdalla
Abdalla wants to transfer 20 riyals to Sana
Will our code always work?
Deadlocks - Account Transfer Example Resolution

Sana -> Abdalla
\[ \text{synchronized}(\text{SanaAccount}) \]
\[ \text{synchronized}(\text{AbdallaAccount}) \]

\[ \text{if } (\text{SanaAccount}.\text{getbal}() > \text{val}) \]
\[ \text{SanaAccount}.\text{post}(-\text{val}) \]
\[ \text{AbdallaAccount}.\text{post}(\text{val}) \]

Abdalla -> Sana
\[ \text{synchronized}(\text{SanaAccount}) \]

\[ \text{if } (\text{AbdallaAccount}.\text{getbal}() > \text{val}) \]
\[ \text{AbdallaAccount}.\text{post}(-\text{val}) \]
\[ \text{SanaAccount}.\text{post}(-\text{val}) \]

Time

Sana wants to transfer 10 riyals to Abdalla
Abdalla wants to transfer 20 riyals to Sana

Fix: Apply Ranking to shared resources and locks should be acquired in order based on rank

Suppose Sana’s account has higher rank
Outline

• Project 2 Objectives Recap
• Dining Philosophers & Deadlocks
• Synchronization in Project 2
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Project 2: Synchronization

- Reader & Writer clients acquire lock before invoking the method, and release the lock after they are done

1. **Reader:**
   - Reader first requests a **read/non-exclusive/shared lock**
   - Multiple readers can acquire a read lock simultaneously

2. **Writer:**
   - Writer first requests a **write/exclusive lock**
   - Only **one writer can acquire a write lock** at a time

3. **Order:**
   - Readers and writers are queued and served in the **FIFO order**
Project 2: Synchronization

Naming Server grants a reader or writer read/shared locks on all the directories in the path to prevent modifications.

Naming Server then grants the requester a shared lock if it is a reader or an exclusive lock if it is a writer to the file.
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Thread Synchronization in Java

• Synchronized Block
  • Using synchronized keyword to define a critical section

• Lock APIs
  • Using Lock interface in the java.util.concurrent.lock package

• Semaphores
  • Using Semaphore class in the java.util.concurrent.Semaphore package
Thread Synchronization in Java

• Synchronized Block
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• Semaphores
  • Using `Semaphore` class in the `java.util.concurrent.Semaphore` package
Synchronized Block

```java
public boolean transfer(Account2 from, Account2 to, int val) {
    Account2 first = (from.rank > to.rank) ? from : to;
    Account2 second = (from.rank > to.rank) ? to : from;
    synchronized(first) {
        synchronized(second) {
            if (from.getbal() > val)
                from.post(-val);
            else {
                return false;
            }
            to.post(val);
            return true;
        }
    }
}
```
Thread Synchronization in Java

- Synchronized Block
  - Using synchronized keyword to define a critical section

- Lock APIs
  - Using Lock interface in the java.util.concurrent.lock package

- Semaphores
  - Using Semaphore class in the java.util.concurrent.Semaphore package
Locks—Lock Usage

Lock lock = ...

lock.lock();
try {
    // manipulate protected state
} finally {
    lock.unlock();
}

The thread that calls Lock first becomes the owner, and it is the only thread that can release the lock.
## Locks vs. Synchronized blocks

<table>
<thead>
<tr>
<th>Synchronized Blocks</th>
<th>Locks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully contained <strong>within a method</strong></td>
<td>Can have <strong>lock()</strong> and <strong>unlock()</strong> operation in separate methods</td>
</tr>
<tr>
<td>Rigid, any thread can acquire the lock once released, <strong>no preference</strong> can be specified</td>
<td>Flexible; we can <strong>prioritize</strong> waiting threads for example</td>
</tr>
<tr>
<td><strong>A thread</strong> always gets <strong>blocked</strong> if it can't get an access to the synchronized block</td>
<td>The Lock API provides <strong>tryLock() non-blocking</strong> method. The thread acquires lock only if it's available and not held by any other thread.</td>
</tr>
<tr>
<td><strong>A thread</strong> which is in “<strong>waiting</strong>” state to acquire the access to synchronized block, <strong>can't be interrupted</strong></td>
<td>The Lock API provides a method <strong>lockInterruptibly()</strong> which <strong>can</strong> be used to <strong>interrupt the thread when it's waiting</strong> for the lock</td>
</tr>
</tbody>
</table>
# Locks—Lock API

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>void lock()</td>
<td>Acquire the lock if it's available; if the lock isn't available a thread gets blocked until the lock is released</td>
</tr>
<tr>
<td>void lockInterruptibly()</td>
<td>similar to the <code>lock()</code>, but it allows the blocked thread to be interrupted and resume the execution through a thrown <code>java.lang.InterruptedException</code></td>
</tr>
<tr>
<td>boolean tryLock()</td>
<td>non-blocking version of <code>lock()</code> method; it attempts to acquire the lock immediately. It returns true if locking succeeds; false otherwise.</td>
</tr>
<tr>
<td>boolean tryLock(long timeout, TimeUnit timeUnit)</td>
<td>similar to <code>tryLock()</code>, except it waits up the given timeout before giving up trying to acquire the <code>Lock</code></td>
</tr>
<tr>
<td>void unlock()</td>
<td>unlocks the <code>Lock</code> instance</td>
</tr>
</tbody>
</table>
Locks— Read/Write Locks

The rules for acquiring the ReadLock or WriteLock by a thread:

• **Read Lock** (Shared)— If no thread acquired the write lock or requested for it, multiple threads can acquire the read lock.

• **Write Lock** (Exclusive)— If no threads are reading or writing, only one thread can acquire the write lock.
Locks–
Read/Write Locks

ReadWriteLock Interface

<table>
<thead>
<tr>
<th>Modifier and Type</th>
<th>Method and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lock</td>
<td>readLock()</td>
</tr>
<tr>
<td></td>
<td>Returns the lock used for reading.</td>
</tr>
<tr>
<td>Lock</td>
<td>writeLock()</td>
</tr>
<tr>
<td></td>
<td>Returns the lock used for writing.</td>
</tr>
</tbody>
</table>

Lock Interface

<table>
<thead>
<tr>
<th>Modifier and Type</th>
<th>Method and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>void</td>
<td>lock()</td>
</tr>
<tr>
<td></td>
<td>Acquires the lock.</td>
</tr>
<tr>
<td>void</td>
<td>lockInterruptibly()</td>
</tr>
<tr>
<td></td>
<td>Acquires the lock unless the current thread is interrupted.</td>
</tr>
<tr>
<td>Condition</td>
<td>newCondition()</td>
</tr>
<tr>
<td></td>
<td>Returns a new Condition instance that is bound to this Lock instance.</td>
</tr>
<tr>
<td>boolean</td>
<td>tryLock()</td>
</tr>
<tr>
<td></td>
<td>Acquires the lock only if it is free at the time of invocation.</td>
</tr>
<tr>
<td>boolean</td>
<td>tryLock(long time, TimeUnit unit)</td>
</tr>
<tr>
<td></td>
<td>Acquires the lock if it is free within the given waiting time and the current thread has not been interrupted.</td>
</tr>
<tr>
<td>void</td>
<td>unlock()</td>
</tr>
<tr>
<td></td>
<td>Releases the lock.</td>
</tr>
</tbody>
</table>

ReentrantReadWriteLock Class

<table>
<thead>
<tr>
<th>Method and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>getOwner()</td>
</tr>
<tr>
<td>Returns the thread that currently owns the write lock, or null if not owned.</td>
</tr>
<tr>
<td>getQueuedReaderThreads()</td>
</tr>
<tr>
<td>Returns a collection containing threads that may be waiting to acquire the read lock.</td>
</tr>
<tr>
<td>getQueuedThreads()</td>
</tr>
<tr>
<td>Returns a collection containing threads that may be waiting to acquire either the read or write lock.</td>
</tr>
<tr>
<td>getQueuedWriterThreads()</td>
</tr>
<tr>
<td>Returns a collection containing threads that may be waiting to acquire the write lock.</td>
</tr>
<tr>
<td>getQueueLength()</td>
</tr>
<tr>
<td>Returns an estimate of the number of threads waiting to acquire either the read or write lock.</td>
</tr>
<tr>
<td>getReadHoldCount()</td>
</tr>
<tr>
<td>Queries the number of reentrant read holds on this lock by the current thread.</td>
</tr>
<tr>
<td>getReadCount()</td>
</tr>
<tr>
<td>Queries the number of read locks held for this lock.</td>
</tr>
<tr>
<td>getWaitingThreads(Condition condition)</td>
</tr>
<tr>
<td>Returns a collection containing those threads that may be waiting on the given condition associated with the write lock.</td>
</tr>
<tr>
<td>getWaitQueueLength(Condition condition)</td>
</tr>
<tr>
<td>Returns an estimate of the number of threads waiting on the given condition associated with the write lock.</td>
</tr>
<tr>
<td>getWriteHoldCount()</td>
</tr>
<tr>
<td>Queries the number of reentrant write holds on this lock by the current thread.</td>
</tr>
<tr>
<td>hasQueuedRead(Thread thread)</td>
</tr>
<tr>
<td>Queries whether the given thread is waiting to acquire either the read or write lock.</td>
</tr>
<tr>
<td>hasQueuedReads()</td>
</tr>
<tr>
<td>Queries whether any threads are waiting to acquire the read or write lock.</td>
</tr>
<tr>
<td>hasWaiters(Condition condition)</td>
</tr>
<tr>
<td>Queries whether any threads are waiting on the given condition associated with the write lock.</td>
</tr>
<tr>
<td>isFair()</td>
</tr>
<tr>
<td>Returns true if this lock has fairness set true.</td>
</tr>
<tr>
<td>isWriterLocked()</td>
</tr>
<tr>
<td>Queries if the write lock is held by any thread.</td>
</tr>
<tr>
<td>isWriterLockedByCurrentThread()</td>
</tr>
<tr>
<td>Queries if the write lock is held by the current thread.</td>
</tr>
<tr>
<td>readLock()</td>
</tr>
<tr>
<td>Returns the lock used for reading.</td>
</tr>
<tr>
<td>toString()</td>
</tr>
<tr>
<td>Returns a string identifying this lock, as well as its lock state.</td>
</tr>
<tr>
<td>writeLock()</td>
</tr>
<tr>
<td>Returns the lock used for writing.</td>
</tr>
</tbody>
</table>
Locks—Using ReentrantReadWriteLock Class

```java
ReadWriteLock readWriteLock = new ReentrantReadWriteLock();

readWriteLock.readLock().lock();

// multiple readers can enter this section
// if not locked for writing,
// and not writers waiting to lock for writing.

readWriteLock.readLock().unlock();

readWriteLock.writeLock().lock();

// only one writer can enter this section,
// and only if no threads are currently reading.

readWriteLock.writeLock().unlock();
```
Locks—ReentrantReadWriteLock Class

Example

```java
public class SynchronizedHashMapWithReadWriteLock {

    Map<String, String> syncHashMap = new HashMap<>();
    ReadWriteLock lock = new ReentrantReadWriteLock();

    Lock writeLock = lock.writeLock();
    Lock readLock = lock.readLock();

    //...

    public void put(String key, String value) {
        try {
            writeLock.lock();
            syncHashMap.put(key, value);
        } finally {
            writeLock.unlock();
        }
    }
}
```
Locks—ReentrantReadWriteLock Class

Example

```java
public String remove(String key){
    try {
        writeLock.lock();
        return syncHashMap.remove(key);
    } finally {
        writeLock.unlock();
    }
}
```

```java
public String get(String key){
    try {
        readLock.lock();
        return syncHashMap.get(key);
    } finally {
        readLock.unlock();
    }
}
```
Locks– Locks with Conditions

- The `Condition class` provides the ability for a thread to *wait for some condition to occur* while executing the critical section.
- This can occur when a thread *acquires the access to the critical section but doesn't have the necessary condition* to perform its operation. 
- Traditionally Java provides `wait()`, `notify()` and `notifyAll()` methods for thread intercommunication.
  - *Conditions* have similar mechanisms, but in addition, we can specify multiple conditions.

Example:
# Locks—Locks with Conditions

<table>
<thead>
<tr>
<th>Modifier and Type</th>
<th>Method and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>void</td>
<td>await()</td>
</tr>
<tr>
<td></td>
<td>Causes the current thread to wait until it is signalled or <strong>interrupted</strong>.</td>
</tr>
<tr>
<td>boolean</td>
<td>await(long time, TimeUnit unit)</td>
</tr>
<tr>
<td></td>
<td>Causes the current thread to wait until it is signalled or interrupted, or the specified waiting time elapses.</td>
</tr>
<tr>
<td>long</td>
<td>awaitNanos(long nanosTimeout)</td>
</tr>
<tr>
<td></td>
<td>Causes the current thread to wait until it is signalled or interrupted, or the specified waiting time elapses.</td>
</tr>
<tr>
<td>void</td>
<td>awaitUninterruptibly()</td>
</tr>
<tr>
<td></td>
<td>Causes the current thread to wait until it is signalled.</td>
</tr>
<tr>
<td>boolean</td>
<td>awaitUntil(Date deadline)</td>
</tr>
<tr>
<td></td>
<td>Causes the current thread to wait until it is signalled or interrupted, or the specified deadline elapses.</td>
</tr>
<tr>
<td>void</td>
<td>signal()</td>
</tr>
<tr>
<td></td>
<td>Wakes up one waiting thread.</td>
</tr>
<tr>
<td>void</td>
<td>signalAll()</td>
</tr>
<tr>
<td></td>
<td>Wakes up all waiting threads.</td>
</tr>
</tbody>
</table>
public class ReentrantLockWithCondition {

    Stack<String> stack = new Stack<>();
    int CAPACITY = 5;

    ReentrantLock lock = new ReentrantLock();
    Condition stackEmptyCondition = lock.newCondition();
    Condition stackFullCondition = lock.newCondition();
}
public void pushToStack(String item){
    try {
        lock.lock();
        while(stack.size() == CAPACITY) {
            stackFullCondition.await(); //wait for a signal that the stack isn't full
        }
        stack.push(item);
        stackEmptyCondition.signalAll(); //Send a signal that the stack isn't empty
    } finally {
        lock.unlock();
    }
}
public String popFromStack() {
    try {
        lock.lock();
        while (stack.size() == 0) {
            stackEmptyCondition.await(); // wait for a signal that the stack isn't empty
        }
        return stack.pop();
    } finally {
        stackFullCondition.signalAll(); // Send a signal that the stack isn't full
        lock.unlock();
    }
}
Thread Synchronization in Java

• Synchronized Block
  • Using synchronized keyword to define a critical section

• Lock APIs
  • Using `Lock` interface in the `java.util.concurrent.lock` package

• Semaphores
  • Using `Semaphore` class in the `java.util.concurrent.Semaphore` package
Semaphores

• Work on the **concept of permits**
• A semaphore is **initialized** with a **certain number of permits**, which
  • depends on the problem at hand
  • usually set to the number of resources available
• When a thread wants to access a shared resource, it acquires a permit and releases it when it is done
• Threads that couldn’t acquire permits are **queued**

There are 10 tables in a restaurant, and you are managing access to these tables

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Carnegie Mellon University Qatar
## Semaphores - API

<table>
<thead>
<tr>
<th>Method/Constructor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semaphore(int permits, <strong>boolean fair</strong>)</td>
<td>Creates a Semaphore with the given number of permits and the given fairness setting</td>
</tr>
<tr>
<td><strong>acquire()</strong></td>
<td>Acquires a permit; blocks until one is available</td>
</tr>
<tr>
<td><strong>acquire(int permits)</strong></td>
<td>Acquires the given number of permits from this semaphore, blocking until all are available</td>
</tr>
<tr>
<td><strong>tryAcquire()</strong></td>
<td>Return true if a permit is available immediately and acquire it; otherwise return false</td>
</tr>
<tr>
<td><strong>availablePermits()</strong></td>
<td>Return number of current permits available</td>
</tr>
<tr>
<td><strong>drainPermits()</strong></td>
<td>Acquires and returns all permits that are immediately available</td>
</tr>
</tbody>
</table>

*Blocking* ensures the order in which the queued requesting threads acquire permits (based on their waiting time)
**Binary Semaphores - Mutex**

**Mutex** acts as a binary semaphore (i.e. only one permission at a time),

We can use it to implement **mutual exclusion**.

```java
Semaphore mutex = new Semaphore(1);
try {
    mutex.acquire();
    assertEquals(0, mutex.availablePermits());
} catch (InterruptedException e) {
    e.printStackTrace();
} finally {
    mutex.release();
    assertEquals(1, mutex.availablePermits());
}
```
Binary Semaphores vs. Locks

- Is a type of signaling mechanism.
- Provides a non-ownership-based signaling mechanism for mutual exclusion.
- Any thread can call Acquire or Release.
- Therefore, any thread can release the permit for a deadlock recovery of a binary semaphore.

- A higher-level synchronization mechanism by allowing a custom implementation of a locking mechanism and deadlock recovery.
- A Semaphore can be used as a queue of blocked threads that are waiting for a condition to be true.

- Is a locking mechanism.
- Provides a reentrant mutual exclusion with owner-based locking capabilities and is useful as a simple mutex.
  - The thread who has the lock calls unlock.

- On the contrary, deadlock recovery is difficult to achieve in the case of a reentrant lock. For instance, if the owner thread of a reentrant lock goes into sleep or infinite wait, it won't be possible to release the resource, and a deadlock situation will result.

- A low-level synchronization with a fixed locking mechanism.
Credits

This recitation was inspired by multiple Baeldung tutorials:

Readers-writers problem
The Dining Philosophers Problem
Locks in Java
Semaphores in Java
Semaphores in Java (2)
Mutex

https://crystal.uta.edu/~ylei/cse6324/data/semaphore.pdf