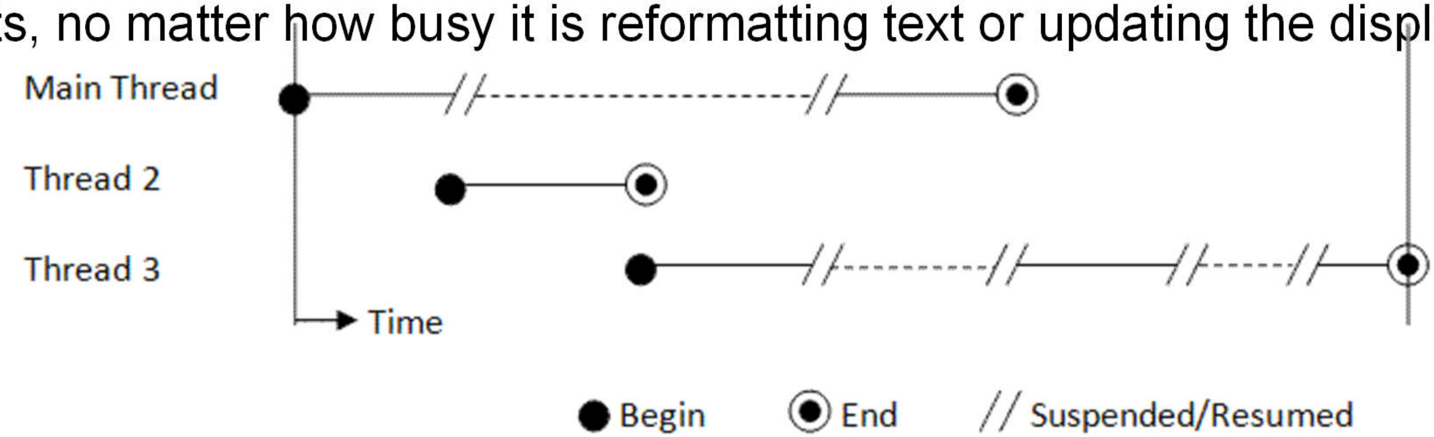
Concurrency

- Threads
- Synchronization
- Memory Consistency
- High-Level Concurrency

Threads

Introduction

- Even a single application is often expected to do more than one thing at a time → *concurrency programming*
  - A streaming audio application must simultaneously read the digital audio off the network, decompress it, manage playback, and update its display
  - A word processor should always be ready to respond to keyboard and mouse events, no matter how busy it is reformatting text or updating the display



Processes vs Threads

- A *process* or program has its own address space and control blocks
  - It is called heavyweight because it consumes a lot of system resources
  - Within a process or program, we can run multiple threads concurrently to improve the performance
- *Threads* are lightweight and run inside a single process
  - They share the same address space, the resources allocated and the environment of that process
  - It is lightweight because it runs within the context of a heavyweight process and takes advantage of the resources allocated for that program and the program’s environment
  - A thread must carve out its own resources within the running process: its own stack, registers and program counter
- A program when started always has a default (or main) process and thread

Creating a Thread

- By implementing `Runnable` interface
  - ```
    Thread newThread = new Thread(new Runnable() {
       @Override
       public void run() {
          System.out.println("New thread...");
       }
    });
    newThread.start();
    ```
  - ```
    new Thread(() -> {
       System.out.println("New thread...");
    }).start();
    ```
- By extending `Thread` class
  - ```
    Thread newThread = new Thread() {
       @Override
       public void run() {
          System.out.println("New thread...");
       }
    };
    newThread.start();
    ```
    ```

Passing Parameters

- ```java
  for (int i = 0; i < 10; i++) {
     new Thread(new Runnable() {
        private int ii;

        @Override
        public void run() {
           System.out.println(ii);
        }

        public Runnable pass(int ii) {
           this.ii = ii;
           return this;
        }
     }.pass(i)).start();
  }
  ```
- ```java
  for (int i = 0; i < 10; i++) {
     final int ii = i;
     new Thread(() -> System.out.println(ii)).start();
  }
  ```

`Thread` Class

- Main methods

Method	Description
`void start()`	Starts a new thread
`void interrupt()`	Sets the `interrupted` flag, and triggers an `InterruptedException` in the thread if a supporting method is under execution
`void join()`	Allows one thread to wait for the completion of another
`void wait([long millis])`	Puts the current thread into sleep until another thread wakes it up
`void notify()` `void notifyAll()`	Wakes one/all other threads that is/are waiting
`void setPriority(int priority)`	Changes the priority of thread to the given value
`static void sleep(long millis, [long nanos])`	Pauses the thread for a given period
`static boolean interrupted()`	Checks if the `interrupted` flag has been set
`static Thread currentThread()`	Gets the `Thread` object for the current thread

Interrupting a Thread

- To response to the `interrupt()` request:
  - Handle `InterruptedException`
  - Check for the `interrupted` flag
- Example:
  - ```
    public void run() {
       for (int i = 0; i < 100000; i++) {
          // do something...
          if (Thread.interrupted()) return;
       }

       try {
          Thread.sleep(3000);
       } catch(InterruptedException e) {
          return;
       }
    }
    ```
    ```

Thread's Priority

- Thread's priority is an integer in the range 1 to 10 (larger the higher priority), but 3 constants are commonly used:
  - `MIN_PRIORITY` = 1
  - `NORM_PRIORITY` = 5 (default)
  - `MAX_PRIORITY` = 10
- Example:
  - `thread.setPriority(Thread.MAX_PRIORITY);`

Exercise

- Write a program with 2 threads:
    - One thread regularly prints the current time
    - One thread reads numbers and calculate their squares

Synchronization

Overview

- There are a lot of reasons that the execution of tasks in different threads need to be synchronized:
  - A task in one thread need the result produced by another task in another thread
    - Let's think about multiple chefs in preparing dishes for a meal
  - A shared resource cannot be used by 2 (or more) different threads at the same time
    - Let's think about books in a library
- Synchronization is about the capability to control the execution of multiple threads

`join()` Method

- If invoked:
  - The current thread goes into the wait state and remains until the thread on which the `join()` method is invoked has achieved its dead state
  - If interruption of the thread occurs, then it throws the `InterruptedException`
- Useful when a thread wants to wait until the result from another is available
- Example:
  - ```
    Thread t = new Thread(() -> {
        // do something in new thread...
        result = 1000;
    });
    t.start();

    // do something in main thread...

    t.join();
    System.out.print(result);
    ```
    ```

Critical Sections

- Threads communicate primarily by sharing access to fields and the objects reference fields refer to → resource access conflicts
  - Resources can be interpreted in a generalized meaning, which can be memory blocks, peripherals, files, network connections, or code segments,…
- Example:

Thead 1	Thead 2	Values
		`n ← 10`
`t = n;`		`t#1 ← 10`
	`t = n;`	`t#2 ← 10`
`t += 1;`		`t#1 ← 11`
	`t += 2;`	`t#2 ← 12`
`n = t;`		`n ← 11`
	`n = t;`	**`n ← 12`**

time

- Access to resources need to be controlled ➔ *Critical sections (CS)*

Shared Memory

- Memory model:
  - Local variables, method parameters, exception handler parameters are stored in the stack memory
  - All objects and their instance fields, static fields are stored in the heap memory
- The heap memory is shared between threads, the stack is not

Synchronized Methods

- It is not possible for two invocations of synchronized methods on the same object to interleave
  - *Mutual exclusion (mutex)*: When one thread is executing a synchronized method for an object, all other threads that invoke synchronized methods for the same object block until the first thread is done with the object
  - The code in a synchronized method is a critical section and needs to be protected for conflicts
  - Constructors cannot be synchronized
- Example:
  - ```
    class SyncCounter {
        private int counter = 0;

        synchronized void increase1() {
            counter += 1;
        }

        synchronized void increase2() {
            counter += 2;
        }

        synchronized int getValue() {
            return counter;
        }
    }
    ```
    ```

Synchronized Statements

- Possible to make more fine-grained synchronization for code segments
- Example:
    - ```
      class SyncCounter {
          private int counter = 0;

          void increase1() {
              synchronized(this) {
                  counter += 1;
              }
              // do something else...
          }

          void increase2() {
              synchronized(this) {
                  counter += 2;
              }
              // do something else...
          }

          // ...
      }
      ```
      ```

Synchronized Statements using Multiple Locks

```
class SyncVars {
    private int var1 = 0, int var2 = 0;
    private Object lock1 = new Object(), lock2 = new Object();

    void increaseVar1() {
        synchronized(lock1) {
            var1 += 1;
        }
    }

    void increaseVar2() {
        synchronized(lock2) {
            var2 += 1;
        }
    }

    void increaseBoth() {
        synchronized(lock1) {
            var1 += 1;
        }

        // do something else...

        synchronized(lock2) {
            var2 += 1;
        }
    }
}
```

Atomic Actions

- An atomic action is one that effectively happens all at once
  - It cannot stop or be interleaved in the middle: it either happens completely, or it doesn't happen at all
  - No side effects of an atomic action are visible until the action is complete
- A synchronized block is atomic against all other blocks that are synchronized on the same object
- Attention:
  - `boolean`, `char`, `byte`, `short`, `int` assignments are atomic
  - `long` and `double` assignments are not atomic (because of word tearing)
  - Integer increment (`count++`) is not atomic
  - All complex expressions are not atomic

`wait()`, `notify()` and `notifyAll()` Methods (1)

- Calling `wait()` forces the current thread to wait until some other thread invokes `notify()` or `notifyAll()` on the same object
- Useful when a thread wants to wait until when a condition is met
- Example (see `LibraryBorrowing.java`):
  - ```
    void borrowBook(Book book) throws InterruptedException {
       synchronized(book) {
          while (book.isBorrowed()) {
             System.out.println(name + " is waiting for: " + book.getTitle());
             book.wait();
          }
          book.setReader(this);
          System.out.println(name + " borrowed: " + book.getTitle());
       }
    }

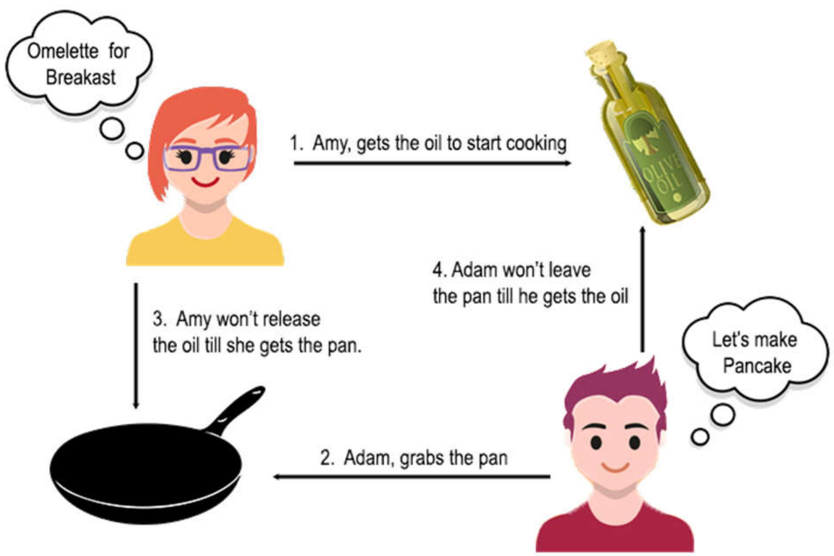
    void returnBook(Book book) {
       synchronized(book) {
          book.setReader(null);
          System.out.println(name + " returned " + book.getTitle());
          book.notify();
       }
    }
    ```
    ```

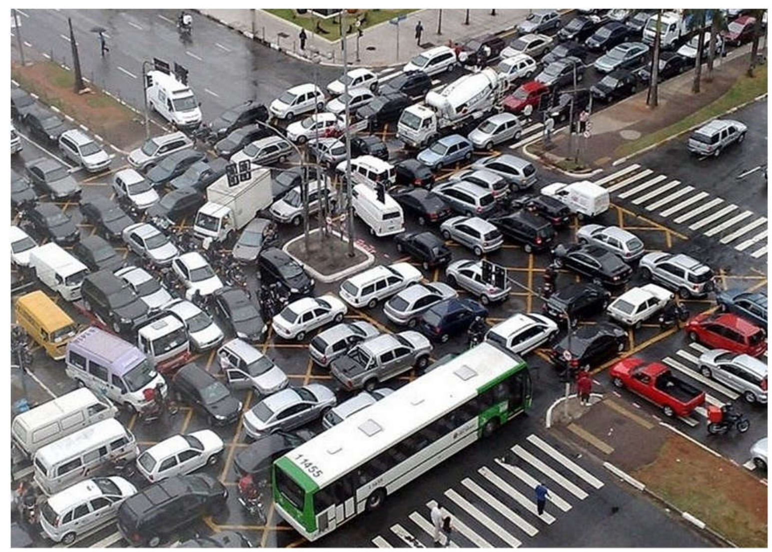
`wait()`, `notify()` and `notifyAll()` Methods (2)

- `notify()` wakes up only one of the waiting threads, while `notifyAll()` wakes up all
- These methods must always be called within a synchronized method or statement
  - `wait()` releases the lock and continues when getting notified
  - `notify()` and `notifyAll()` do not release the lock, so `wait()` can only continue when the notifying thread reaches the end of its synchronized block
- `wait()` must always be put in a loop which terminates only when the condition that the thread is waiting for holds

Deadlocks

- Deadlock occurs when multiple threads need the same locks but obtain them in different order
- Simplest case:
  - Thread 1 waits for Lock A while holding Lock B
  - Thread 2 waits for Lock B while holding Lock A





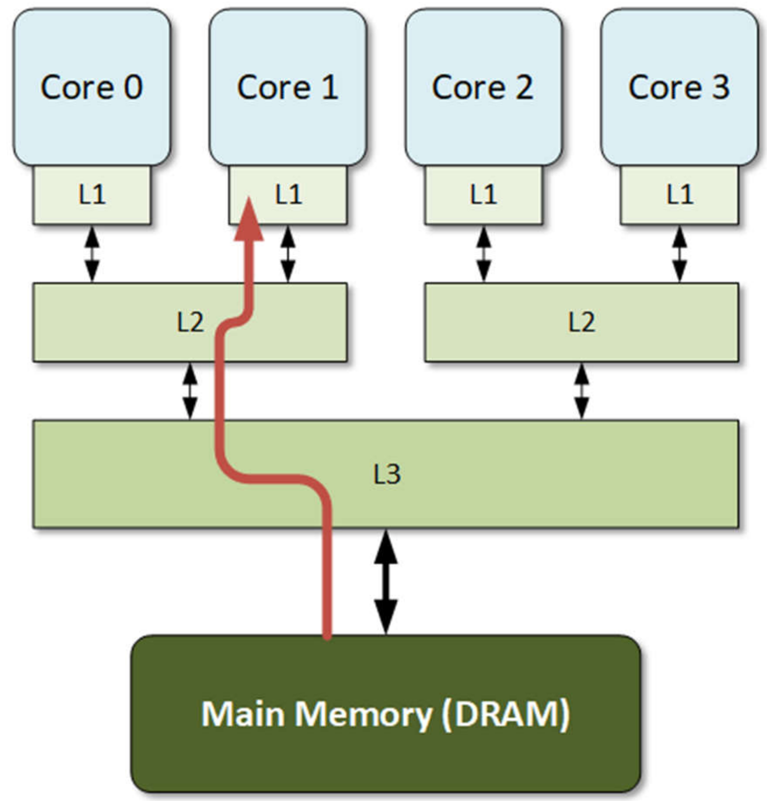
Exercises

1. Write a test program to make sure that the increment is not atomic in Java
2. From the `LibraryBorrowing.java` example, add more books and readers and see the result
3. Implement a blocking queue structure with 2 operations:
   - `put()`: adds an element to the queue (non-blocking)
   - `take()`: removes the first element from the queue, waits if none exists (blocking)
4. Implement a pool of worker threads which pick jobs from a blocking queue to process

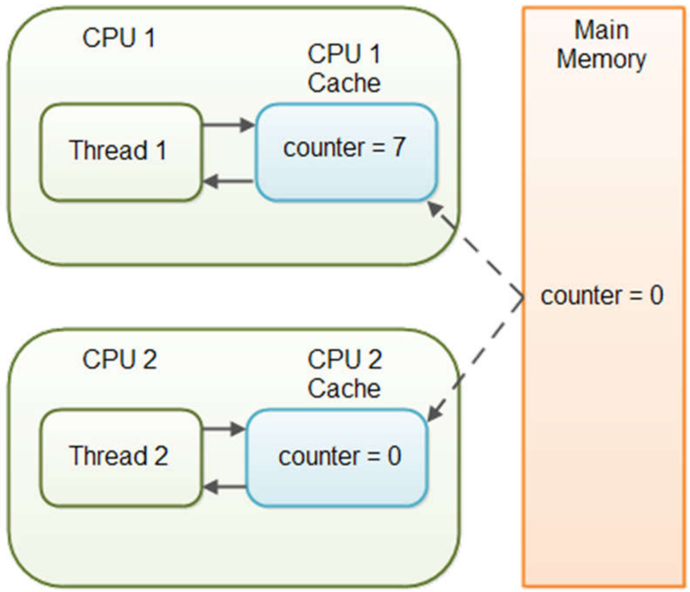
Memory Consistency

Introduction

- For performance optimization, a shared multiprocessor architecture frequently uses the following techniques:
    - Multi-level caching of variables and operations
    - Parallelization
    - Out-of-order execution
- For a single-thread code, it's not necessary to worry about the <u>*cache coherence*</u>
- However, in multi-threading context, the cache coherence may cause memory inconsistency when using shared variables



Variable Visibility Problem



- Each thread may copy the variables into the CPU cache of different CPUs
- Visibility problem: A thread does not see the latest value of a variable because it has not yet been written back to main memory by another thread

Visibility Guarantee

- Declaring a variable `volatile` to guarantee the visibility for other threads of writes to that variable
- `volatile` does not only affect the variable itself, but:
  - If Thread A writes to a `volatile` variable `v` and Thread B subsequently reads `v`, then all variables visible to A before writing to `v`, will also be visible to B after it has read `v`
  - If A reads `v`, then all all variables visible to A when reading `v` will also be re-read from main memory
  - ```
    class MyFraction {
        private volatile int nom;
        private int den;

        void update(int nom, int den) {
            this.den = den;
            this.nom = nom;  // den, nom are all written to the main memory
        }
        double value() {
            double f = nom;  // den, nom are all read from the main memory
            return f / den;
        }
    }
    ```
    ```

Instruction Reordering Problem and Happens-Before Guarantee

- JVM and the CPU are allowed to reorder instructions in the program for performance reasons, as long as the semantic meaning of the instructions remain the same
- But this may introduce problems when one of the variables is `volatile`
  - Example: Imagine if the order of the `update()` and `value()` methods of the `MyFraction` class were changed
- Luckily, the `volatile` keyword gives a ***happens-before*** guarantee:
  - The reads/writes before a write to a `volatile` variable `v` are guaranteed to “happen before” the write to `v`
    - Note that the reordering from after to before is still allowed
  - Reads from and writes to other variables after `v` cannot be reordered to occur before a read of `v`
    - The reordering from before to after is still allowed

`volatile` vs `synchronized`

- `synchronized` also gives visibility, so variables don't need to be `volatile` if they are completely guarded by `synchronized` methods or blocks → `volatile` can generally be done by `synchronized`
  - ```
    class MyFraction {
        private int nom, den;

        synchronized void update(int nom, int den) {
            this.den = den;
            this.nom = nom;
        }
        synchronized double value() {
            return (double)(nom) / den;
        }
    }
    ```
- But `volatile` is cheaper than using `synchronized`
- In general, use `volatile` to let variables be accessed by multiple threads but the atomicity is not required or has already been guaranteed (like in the `MyFraction` class, reads and writes are atomic)
    ```

Immutable Objects

- An immutable object is one that is no longer modified once it has been constructed
  - Since there is no write to the object, it’s thread-safe (but its references are not)
  - Its class has no setters, every modification results in a new object
  - All its fields should be declared `final` and `private`
  - The class should also be declared `final` to disallow subclassing
  - Remind that `String` is immutable
- Example:
  -
```java
final class ImmutableFraction {
    private final int nom, den;

    ImmutableFraction(int nom, int den) {
        this.nom = nom;
        this.den = den;
    }

    ImmutableFraction invert() {
        return new ImmutableFraction(den, nom);
    }
}
```

High Lever Concurrency

Introduction

- Higher-level building blocks are needed for more advanced tasks
- Implemented in the `java.util.concurrent` packages

Atomic Types

- However, suspending and resuming a thread are very expensive and hit the performance
- Low-level atomic types in place of primitive types may help in many circumstances:
  - `AtomicInteger`, `AtomicLong`, `AtomicBoolean`, `AtomicReference`
  - Not every primitive types have corresponding atomic versions
- High-level atomic types:
  - `ConcurrentHashMap` (in place of `HashMap`)
  - `ConcurrentSkipListMap` (in place of `TreeMap`)
  - `ThreadLocalRandom` for thread-safe random number generation

ReentrantLock

- `synchronized` can only be used if the lock acquire and release are close together
- For the case where these two operations are at different places, use `ReentrantLock`:
  - ```java
    class SharedMemory {
        private byte[] mem = new byte[100];
        private Lock mutex = new ReentrantLock();

        byte[] open() {
            mutex.lock();
            return mem;
        }

        void close() {
            mutex.unlock();
        }
    }
    ```
    ```

Semaphore

- For a mutex, only one thread can access a CS, while `Semaphore` allows a fixed number of threads
- Example: A reading room with 20 reading spaces (see full example in `ReadingRoomExample.java`)
  - ```
    class ReadingRoom {
        final int PLACES = 20;
        private Semaphore sem = new Semaphore(PLACES);

        void welcome(Reader r) throws InterruptedException { // blocking
            sem.acquire();
            System.out.println(r.getName() + " came in");
        }

        void onLeave(Reader r) {
            sem.release();
            System.out.println(r.getName() + " left");
        }

        int getReaderCount() {
            return PLACES - sem.availablePermits();
        }

        int getQueueLength() {
            return sem.getQueueLength();
        }
    }
    ```
    ```

`ExecutorService`

- `ExecutorService` automatically provides a pool of threads and an API for assigning tasks to it
- Example: (see full example in `ExecutorServiceExample.java`)
  - ```
    ExecutorService exe = Executors.newFixedThreadPool(5);
    List<Callable<String>> tasks = new ArrayList<>();
    // create tasks...
    List<Future<String>> futures = exe.invokeAll(tasks);

    for (Future<String> f : futures) {
        // use results...
    }
    ```
    ```

Other Pools

- `ExecutorService exe = Executors.newSingleThreadPool()`
  - Create a pool with only a single thread
- `ExecutorService exe = Executors.newCachedThreadPool()`
  - Create a dynamic and unbounded pool that grows from zero thread
  - If a thread is idle for 1min, it may get terminated
- For more control, see `ThreadPoolExecutor` class

Exercises

1. Using `Semaphore`, extend the library example to allow each book title to have multiple instances
2. Use `ExecutorService` to implement a pool of job workers