Concurrency with Threads

Processes

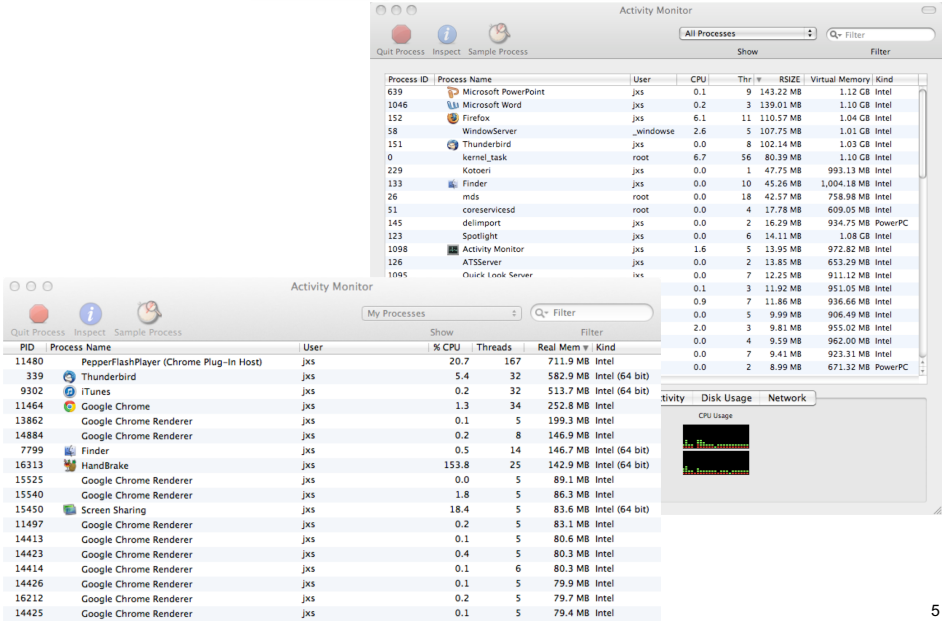
- One of the most important concepts in all modern operating systems
- A process is a container (or execution environment) for a program (software) in execution.
- Any software is executed with one or more processes.
  - Java VM (JVM), MS Word, Excel, PPT, Firefox, iTunes, Google Chrome, etc.

Multi-Tasking (Time Sharing)

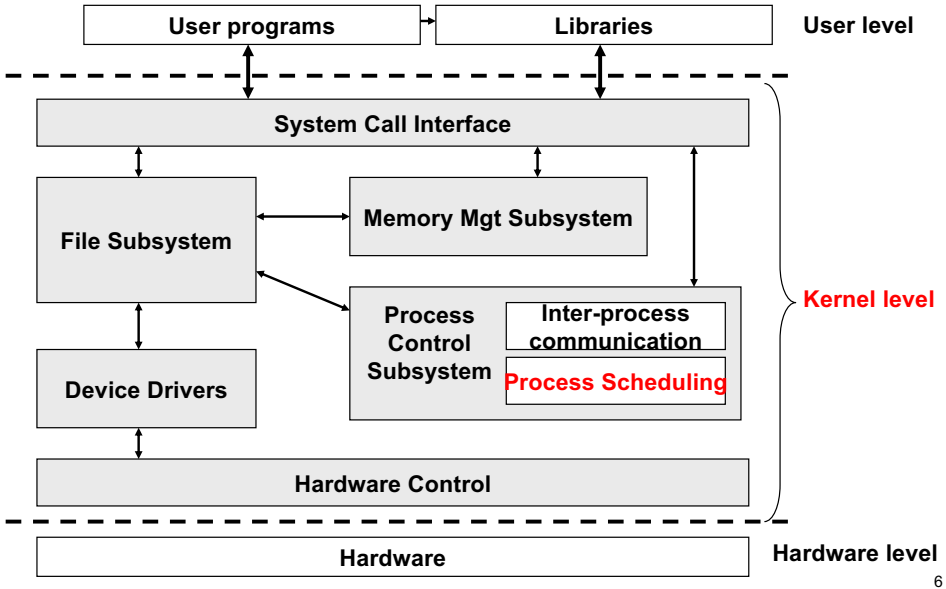
- All modern OSes support multi-tasking.
  - Doing multiple things with multiple processes on a single CPU (more precisely, a single CPU core)
    - e.g., writing a document with MS Word while playing a music with iTunes and downloading files with a Web browser

- At any moment, a single CPU core can execute a single program (process).
- *Pseudo concurrency/parallelism*: An illusion for human eyes as if multiple processes are executed at the same time.
  - OS periodically assigns one process to another to the CPU core.
    - every several tens of milliseconds to several hundreds of milliseconds
    - A CPU core is multiplexed among processes; processes are not executed in a completely parallel manner.

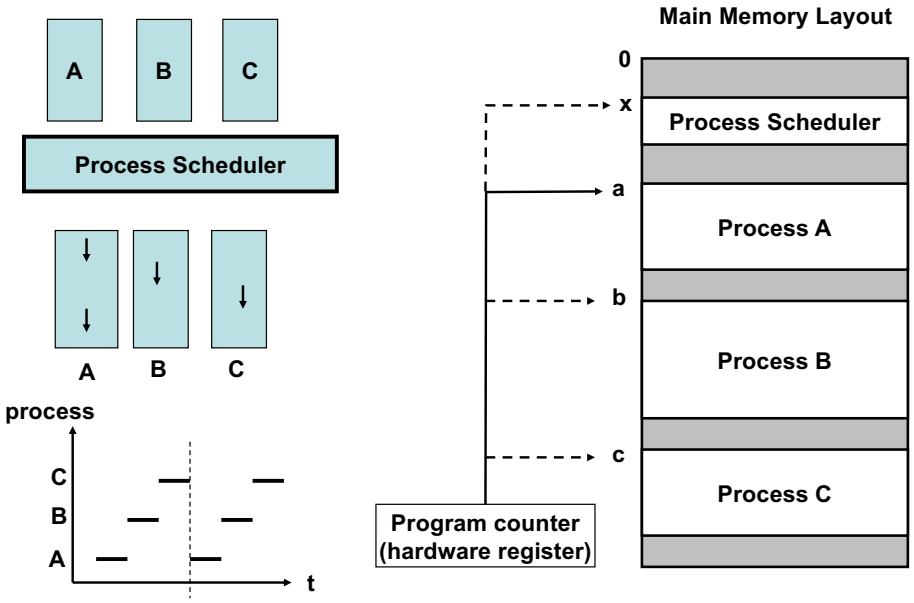
Example Processes



An Architectural View of an OS



Process Scheduling



Why Threads?

- Good old days: Process-based, coarse-grained concurrency was enough
  - e.g., Editing a document while downloading files
- Now: Fine-grained concurrency is required.
  - Each program is required to execute multiple in-program tasks.
    - Doing different things at the same time.
    - Doing the same or a similar thing for multiple clients at the same time.

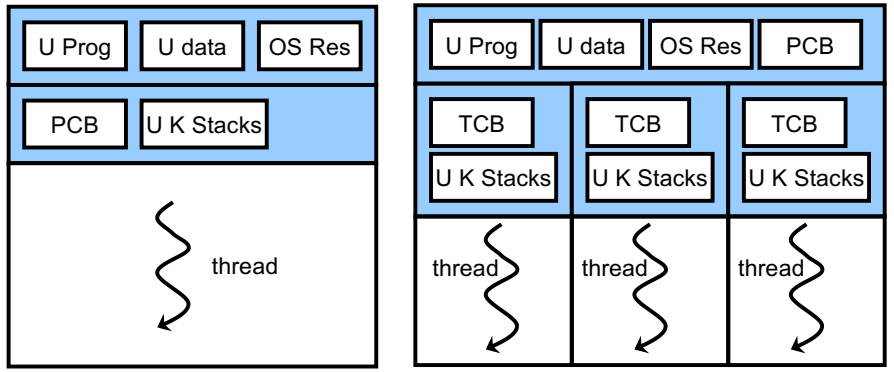
– Each program is required to do different things at the same time.
  - Word
    – Displaying text and images
    – Responding to keystrokes and mouse inputs from the user
    – Downloading fancy document templates from MS web site
    – Performing spelling and grammar checking in the background
  - Web browser
    – Displaying text and images
    – Responding to keystrokes/mouse inputs
    – Checking and downloading software updates
    – Multiple tabs
  - iTunes
    – Playing music
    – Downloading music and its metadata (album's cover img, song titles, lyrics…)
    – Capturing music data (as .mp3 files, for example) from a CD

- # of threads
  – Kernel tasks: 121
  – Dropbox: 103
  – Firefox: 74
  – Thunderbird: 57
  – iTunes: 30
  – MS PPT: 21

– Each program is required to do the same or a similar thing for multiple clients at the same time.
  - Web server
    – Accepts and parses an HTTP request
    – Finds a target file
    – Makes an HTTP message (header, payload, etc.)
    – Returns a target file with the HTTP message

- Assign threads to in-program tasks

- Process-creation is heavyweight.
  – Time-consuming and resource intensive.
    - Creating a process is 30 times slower than creating a thread.
    - Process switching is 5 times slower than thread switching.



Single-threaded (traditional) process

Multi-threaded process

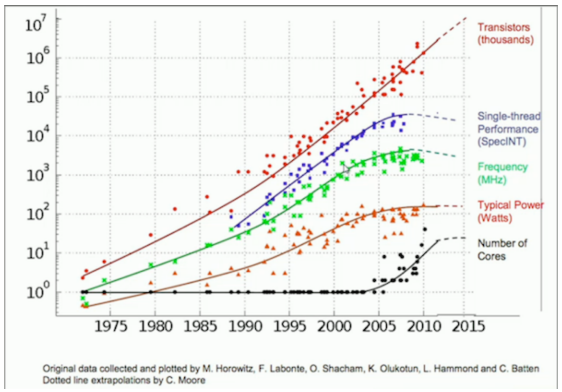
- *Fine-grained* pseudo parallelism: An illusion for human eyes as if multiple threads are executed on a process at the same time.
  - OS periodically assigns one thread to another to the CPU core.
    - A CPU core is multiplexed among processes and threads; processes/threads are not executed in a completely parallel manner on a single CPU core.

Summary: Why Threads?

- Responsiveness/availability
  - Threads allow a program to continue running even if a part of it is blocked for I/O or is performing a long operation.
- Resource sharing
  - Threads share the memory and other resources of a process that they belong to.
- Efficiency
  - Threads are more lightweight than processes.
    - Process creation is expensive.
    - Switching processes is heavyweight.

Other Viewpoints to Threads

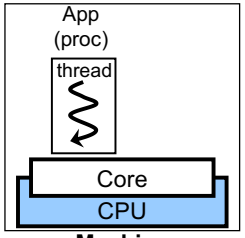
- CPU speed does not increase any more as it did in the past…
  - Physical material barrier to increase clock speed and # of transistors in a CPU
  - Heat (and cooling) and power consumption problems



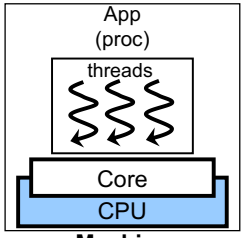
- Each CPU increases its density of cores, not its speed.
  - Intel Core i7: up to 4.0 GHz and up to 8 cores
  - Intel Xeon: up to 4.0 GHz and up to 8 cores
  - Multiple relatively-slower CPU cores for mobile devices to reduce power consumption
    - Amazon Kindle Fire ($50): Quad-core 1.3 GHz
    - Apple iPhone 8/10: 6 cores
- Significant energy consumption and CO_2 emission by data centers
  - Amazon (450K+ servers), Facebook, Google (500K+ servers), Microsoft, Salesforce.com and Yahoo!
  - DCs consumed approx. 1.5% of global electricity usage (‘10).
  - Google paid $2M/mo for electricity bills (‘07).
  - The Info. and Comm. Technology (ICT) industry produced 2% of global CO_2 emission (’07).
    - On par with the aviation industry.
  - IDCs were responsible for 23% of the ICT industry’s emission

- GPUs are designed with a massive # of cores.
  - NVIDIA Tesla K80: 4992 cores
- You are expected to increase your app's performance by increasing its concurrency.
- Ultimate goals of multi-threaded applications: Responsiveness and performance improvement

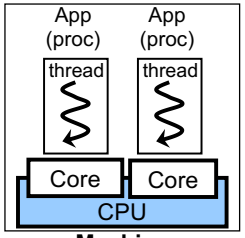
Terminology: Single- or Multi-threaded?



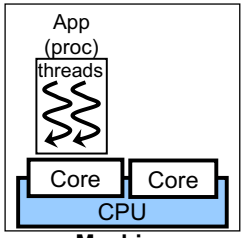
Single-threaded (sequential) app



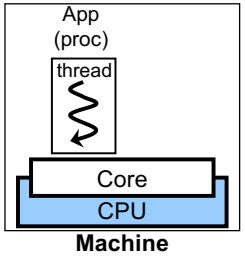
Multi-threaded (concurrent) app



Single-threaded (sequential) apps

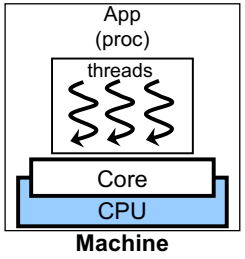


Multi-threaded (concurrent) app



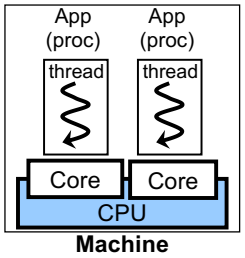
Single-threaded (sequential) app

Executed sequentially



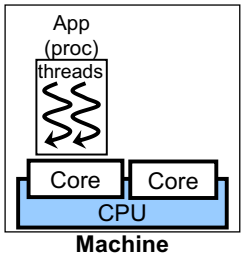
Multi-threaded (concurrent) app

Executed concurrently



Single-threaded (sequential) apps

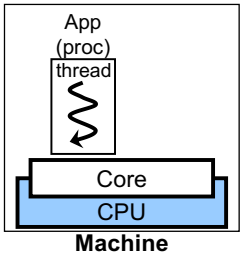
Two apps are executed in parallel. Each app is executed sequentially.



Multi-threaded (concurrent) app

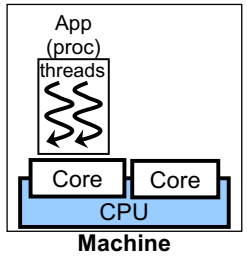
Executed concurrently, not in parallel.

Terminology: Concurrent or Parallel?



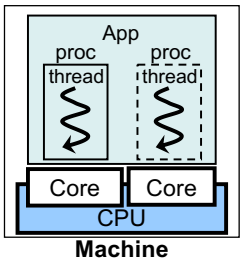
[1] Single-threaded (sequential) app

Not parallel



[2] Multi-threaded (concurrent) app

Not parallel



[3] Multi-threaded (concurrent) app

Parallel

The terms "concurrent" [2] and "parallel" [3] are not always equivalent.

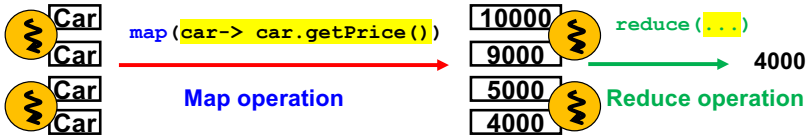
If you think [3] is a special case of [2], you may prefer the term "concurrent."

If you think [2] is a special case of [3], you may prefer the term "parallel."

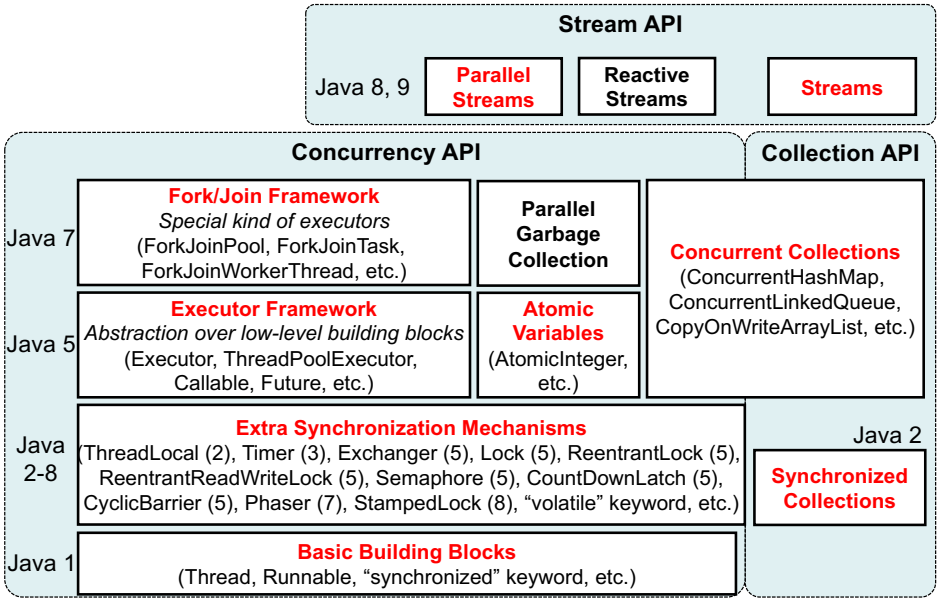
In Java…

- The terms “concurrent” and “parallel” are somewhat mixed up in Java.
  - Java 5 (2004) introduced `java.util.concurrent`, which was further enhanced by Java 6 (2006).
    - “Concurrent” collections such as `ConcurrentHashMap`
    - The Executor framework
      - An extension/abstraction over low-level threads
  - Java 7 (2011)
    - The Fork/Join framework, an extension to the Executor framework
      - The term “parallel” appeared in its documentation, although it was placed in `java.util.concurrent`.
    - “Parallel” garbage collector, which performs garbage collection with multiple threads.
  - Java 8 (2014)
    - “Parallel” streams, which allows for “parallel” (threaded) operations on collections with lambda expressions

- An example of using a parallel stream.
  - ```
    Integer price = cars.stream()
                    .parallel()
                    .map((Car car)-> car.getPrice())
                    .reduce(0, (result, carPrice)->{
                          if(result==0) return carPrice;
                          else if(carPrice < result) return carPrice;
                          else return result;} );
    ```



Concurrency API in Java



Java Threads
    ```

Java Threads

- Every Java program has at least one *thread of control*.
  - **`main()`** runs with a thread on a JVM.
    - When a JVM starts, it implicitly (or automatically) creates the "main" thread.

```
class HelloWorldApp{
  public static void main(String[] args){
    System.out.println("Hello World!");
  } }
```

```
>java HelloWorldApp
```


- If you need extra threads in addition to the main thread, you need to *explicitly* create them.
- 4 things to do:
  - Define a class implementing the **`java.lang.Runnable`** interface
    - **`public abstract void run();`**
  - Write a threaded/concurrent task in **`run()`** in the class
  - Instantiate **`java.lang.Thread`** and associate a Runnable object with the thread
  - Start (call **`start()`** on) the instantiated thread.
    - **`run()`** is automatically called on the thread.

An Example Code: Creating a Thread

- GreetingRunnable.java

```
class GreetingRunnable implements Runnable{
  private String greeting;

  public GreetingRunnable(String aGreeting){
    greeting = aGreeting; }

  public void run(){
    for( int i=0; i<10; i++ ){
      Date now = new Date();
      System.out.println(now + " " + greeting);
    } } }
```

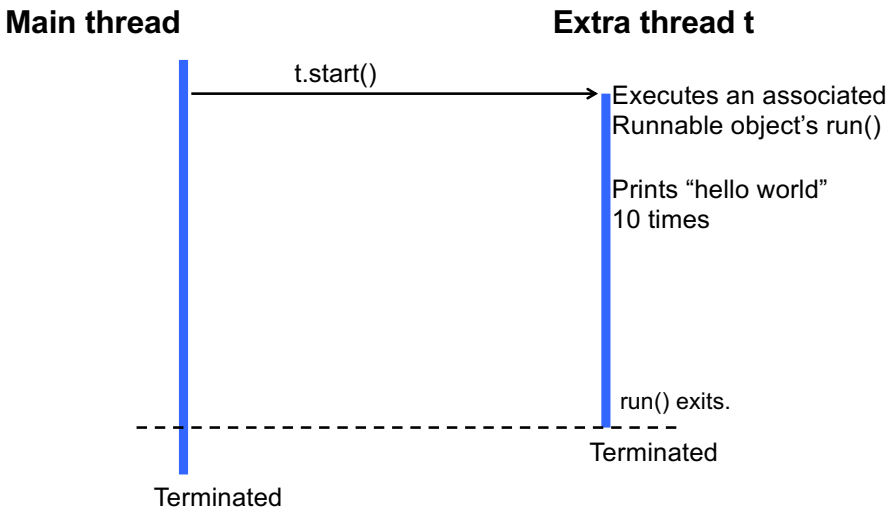
- HelloWorldTest.java

```
main(…){
  GreetingRunnable runnable = new GreetingRunnable("Hello World");
  Thread t = new Thread(runnable);
  t.start(); }
```


Thread.start()

- Creating a Thread object does not mean creating a new thread.
  - It is start() that actually creates a thread.
- start()
  - Allocates memory and initializes a new thread on a JVM.
  - Calls run() of a specified Runnable object.
    - Do not call run() directly, but let start() call run() on behalf of yourself.

Program Execution



- Output:
  - Mon Mar 26 15:14:43 EDT 2007 Hello World
  - Mon Mar 26 15:14:44 EDT 2007 Hello World
  - Mon Mar 26 15:14:45 EDT 2007 Hello World
  - Mon Mar 26 15:14:46 EDT 2007 Hello World
  - Mon Mar 26 15:14:47 EDT 2007 Hello World
  - Mon Mar 26 15:14:48 EDT 2007 Hello World
  - Mon Mar 26 15:14:49 EDT 2007 Hello World
  - Mon Mar 26 15:14:50 EDT 2007 Hello World
  - Mon Mar 26 15:14:51 EDT 2007 Hello World
  - Mon Mar 26 15:14:52 EDT 2007 Hello World

An Example Code: Creating Threads

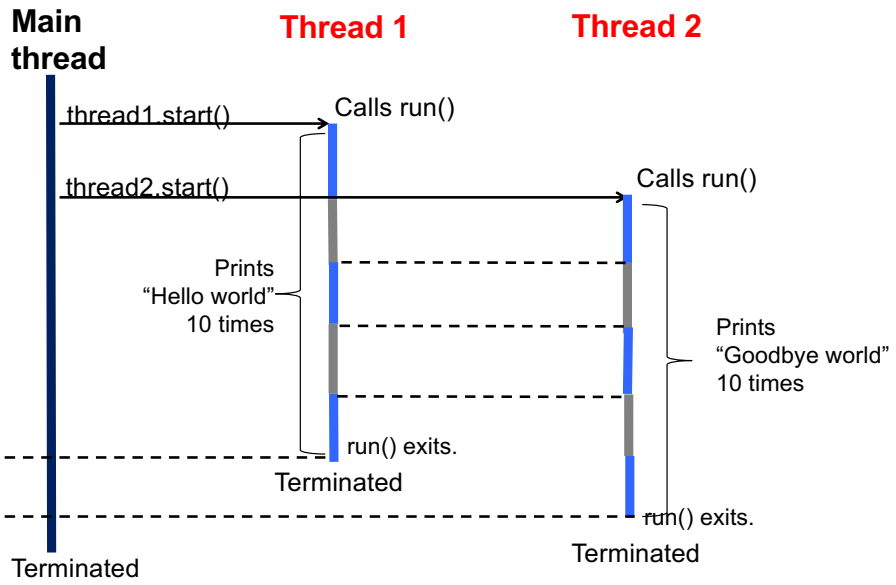
- HelloWorldTest2.java and GreetingRunnable.java

```
main(...){
  GreetingRunnable runnable1 = new GreetingRunnable("Hello World");
  GreetingRunnable runnable2 = new GreetingRunnable("Goodbye World");

  Thread thread1 = new Thread(runnable1);
  Thread thread2 = new Thread(runnable2);

  thread1.start();
  thread2.start();
}
```


Expected Program Execution



A Possible Output

- Output:
  - Mon Mar 26 15:28:45 EDT 2007 Goodbye World
  - Mon Mar 26 15:28:45 EDT 2007 Hello World
  - Mon Mar 26 15:28:46 EDT 2007 Hello World
  - Mon Mar 26 15:28:46 EDT 2007 Goodbye World
  - Mon Mar 26 15:28:47 EDT 2007 Hello World
  - Mon Mar 26 15:28:47 EDT 2007 Goodbye World
  - Mon Mar 26 15:28:48 EDT 2007 Goodbye World
  - Mon Mar 26 15:28:48 EDT 2007 Hello World
  - Mon Mar 26 15:28:49 EDT 2007 Goodbye World
  - Mon Mar 26 15:28:49 EDT 2007 Hello World
  - Mon Mar 26 15:28:50 EDT 2007 Goodbye World
  - Mon Mar 26 15:28:50 EDT 2007 Hello World
  - Mon Mar 26 15:28:51 EDT 2007 Goodbye World
  - Mon Mar 26 15:28:51 EDT 2007 Hello World
  - Mon Mar 26 15:28:52 EDT 2007 Hello World
  - Mon Mar 26 15:28:52 EDT 2007 Goodbye World
  - Mon Mar 26 15:28:53 EDT 2007 Hello World

- Two message sets (Hello and Goodbye) are NOT exactly interleaved.

The Order of Thread Execution

- JVM's thread scheduler gives you NO guarantee about the order of thread execution.

- There are always slight variations in the time to execute a threaded task
  - especially when calling OS system calls (typically I/O related system calls)

- Expect that the order of thread execution is somewhat random.

Exercise

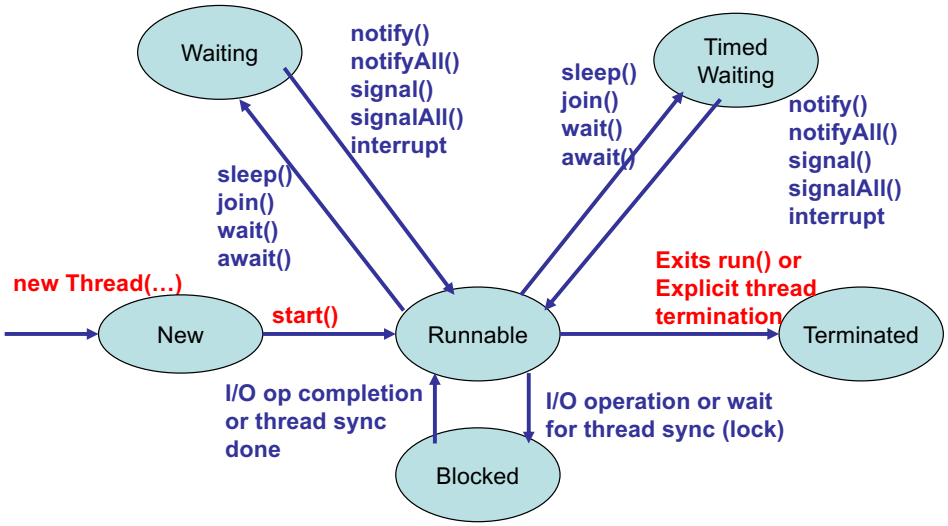
- Modify HelloWorldTest2.java;
  - Replace the following 4 lines
    - `Thread thread1 = new Thread(runnable1);`
    - `Thread thread2 = new Thread(runnable2);`
    - `thread1.start();`
    - `thread2.start();`
  - with the following 2 lines:
    - runnable1.run();
    - runnable2.run();

- What does the program output?

- Modify HelloWorldTest2.java;
  - Replace the following 4 lines
    - `Thread thread1 = new Thread(runnable1);`
    - `Thread thread2 = new Thread(runnable2);`
    - `thread1.start();`
    - `thread2.start();`
  - with the following 2 lines:
    - runnable1.run();
    - runnable2.run();

- Output: "Hello World" in 10 lines, followed by "Good Bye World" in 10 lines.
  - The program runs sequentially, not concurrently.

States of a Thread



- New
  - A Thread object is created. start() has not been called on the object yet.
- Runnable
  - Java does not distinguish ready-to-run and running. A running thread is still in the Runnable state.
- Terminated/dead
  - A thread automatically dies when run() returns.

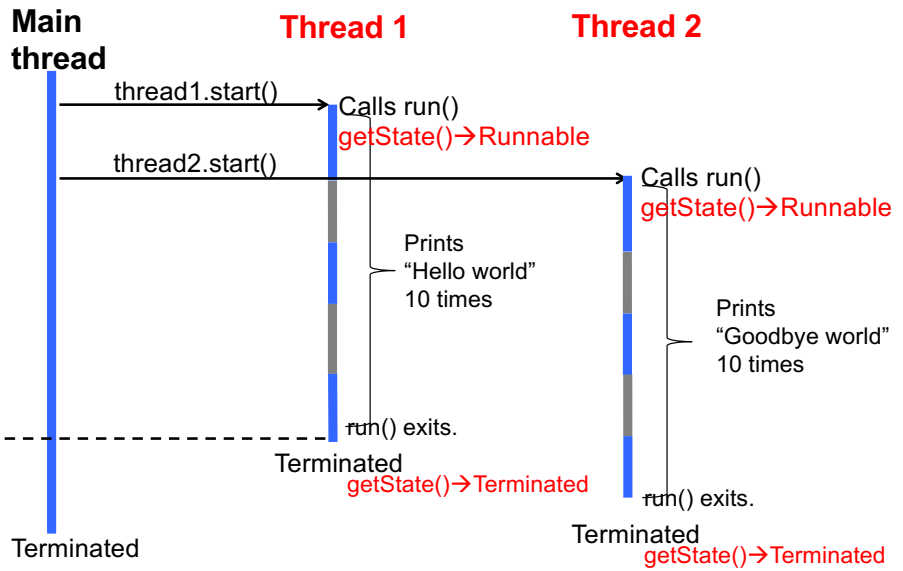

- ```
  public class Thread{
      public enum State{
         NEW, RUNNABLE, BLOCKED, WAITING,
         TIMED_WAITING, TERMINATED }

      public Thread.State getState()

      public boolean isAlive()
  ```

- Alive
  - in the Runnable, Blocked, Waiting or Timed Waiting state.
  - isAlive() is usually used to poll/check a thread to see if it is terminated.

Program Execution w/ HelloWorldTest2


  ```