CS x55: DISTRIBUTED SYSTEMS  [THREADS]

Threads: Reap What You Sow
Care to use more than a core?
Let threads come to the fore
Maximize your utilizations they will
Spurn them at your throughputs’ peril

Shrideep Pallickara
Computer Science
Colorado State University

Frequently asked questions from the previous class survey

- Factory and singletons?
- Why cache the routes?
- ServerSockets
  - What’s this wildcard?
- Term Project
Topics covered in this lecture

- Threads
  - Rationale
  - Contrasting threads with processes
  - Thread Creation

Many hands make light work. John Heywood (1546)
Why should you care about threads?

- CPU clock rates have tapered off
  - Days when you could count on “free” speed-up are long gone
- Manufacturers have transitioned to multicore processors
  - Each with multiple hardware execution pipelines
- A single threaded process can utilize only one of these execution pipelines
  - Reduced throughput
- But more importantly, threads are awesome!

What we will look at

- Threads and its relation to processes
- Thread lifecycle
- Contrasting approaches to writing threads
- Data synchronization and visibility
  - Avoiding race conditions
- Thread safety
- Sharing objects and confinement
- Locking strategies
- Writing thread-safe classes
What are threads?

- Miniprocesses or lightweight processes
- Why would anyone want to have a kind of process within a process?

The main reason for using threads

- In many applications multiple activities are going on at once
  - Some of these may block from time to time

- Decompose application into multiple sequential threads
  - Running concurrently
Isn’t this precisely the argument for processes?

- Yes, but there is a new dimension …
- Threads have the ability to **share the address space** (and all of its data) among themselves
- For several applications
  - Processes (with their separate address spaces) don’t work

Threads execute their own piece of code independently of other threads, but …

- No attempt is made to achieve high-degree of concurrency transparency
  - Especially, not at the cost of performance
- Only maintains information to allow a **CPU to be shared** among several threads
- Thread context
  - CPU Context + Thread Management info
  - List of blocked threads
Information not strictly necessary to manage multiple threads is ignored

- Protecting data against inappropriate accesses by multiple threads in a process?
  - Developers must deal with this

Contrasting items unique & shared across threads

<table>
<thead>
<tr>
<th>Per process items (Shared by threads with a process)</th>
<th>Per thread items (Items unique to a thread)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Address space</td>
<td>Program Counter</td>
</tr>
<tr>
<td>Global variables</td>
<td>Registers</td>
</tr>
<tr>
<td>Open files</td>
<td>Stack</td>
</tr>
<tr>
<td>Child Processes</td>
<td>Stack State</td>
</tr>
<tr>
<td>Pending alarms</td>
<td></td>
</tr>
<tr>
<td>Signals and signal handlers</td>
<td></td>
</tr>
<tr>
<td>Accounting Information</td>
<td></td>
</tr>
</tbody>
</table>
A process with multiple threads of control can perform more than 1 task at a time.

**Threads vs. Multiple Processes**
Why prefer multiple threads over multiple processes?

- Threads are cheaper to create and manage than processes
- Resource sharing can be achieved more efficiently between threads than processes
  - Threads within a process share the address space of the process
- Switching between threads is cheaper than for processes
- **BUT** ... threads within a process are not protected from one another

Other costs for processes

- When a new process is created to perform a task there are other costs
  - In a kernel supporting virtual memory the new process will incur page faults
    - Due to data and instructions being referenced for the first time
- Hardware caches must acquire new cache entries for that particular process
Contrasting the costs for threads [1/2]

- With threads these overheads may also occur, but they are likely to be smaller.
- When thread accesses code & data that was *accessed recently by other threads* in the process?
  - Automatically take advantage of any hardware or main memory caching.

Contrasting the costs for threads [2/2]

- **Switching** between threads is much faster than that between processes.
- This is a cost that is incurred *many times* throughout the lifecycle of the thread or process.
Implications?

- **Performance** of a multithreaded application is seldom worse than a single threaded one
  - Actually, leads to performance gains

- Development requires **additional effort**
  - No automatic protection against each other

Another drawback of processes is the overheads for IPC (Inter Process Communications)

```
<table>
<thead>
<tr>
<th>Process A</th>
<th>Process B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch from user space to kernel space</td>
<td></td>
</tr>
<tr>
<td>Switch context from process A to B</td>
<td></td>
</tr>
<tr>
<td>Operating System</td>
<td></td>
</tr>
<tr>
<td>Switch from kernel space to user space</td>
<td></td>
</tr>
</tbody>
</table>
```
A process in memory

Why each thread needs its own stack [1/2]

- Stack contains one **frame** for each procedure *called but not returned from*

- Frame contains
  - Local variables
  - Procedure's return address
Why each thread needs its own stack

- Procedure X calls procedure Y, Y then calls Z
  - When Z is executing?
    - Frames for X, Y and Z will be on the stack

- Each thread calls different procedures
  - So has a different execution history

Each thread has its own stack

Stack for thread

Kernel
Almost impossible to write programs in Java without threads

- We use multiple threads without even realizing it

Blocking I/O: Reading data from a socket

- Program blocks until data is available to satisfy the `read()` method
- Problems:
  - Data may not be available
  - Data may be delayed (in transit)
  - The other endpoint sends data sporadically
- If program blocks when it tries to read from socket?
  - Unable to do anything else until data is actually available
Three techniques to handle such situations

- **I/O multiplexing**
  - Take all input sources and use system call, `select()`, to notify data availability on any of them

- **Polling**
  - Test if data is available from a particular source
    - System call such as `poll()` is used
    - In Java, `available()` on the `FilterInputStream`

- **Signals**
  - File descriptor representing signal is set
  - *Asynchronous* signal delivered to program when data is available
  - Java does not support this

Writing to a socket may also block

- If there is a **backlog** getting data onto the network
  - Does not happen in fast LAN settings
  - But if it’s over the Internet? Possible.

- So, often handling TCP connections requires both a sender and receiver thread
Writing programs that do I/O in Java?

- Use multiple threads
  - Handle traditional, blocking I/O
- Use the NIO library
- Or both

We are trained to think linearly

- Often don’t see \textit{concurrent paths} our programs may take
- No reason why processes that we conventionally think of as single-threaded should remain so
Thread Abstraction

- A **thread** is a *single execution sequence* that represents a separately schedulable task
  - **Single execution sequence**
    - Each thread executes sequence of instructions – assignments, conditionals, loops, procedures, etc. – just as the sequential programming model
  - **Separately schedulable task**
    - The OS can run, suspend, or resume a thread at any time
Computing the factorial of a number

```java
public class Factorial {
    public static void main(String[] args) {
        int n = Integer.parseInt(args[0]);
        int factorial = 1;
        while (n>1) {
            factorial *= n;
            n--;
        }
        System.out.println(factorial);
    }
}
```

Behind the scenes …

- Instructions are executed as machine-level assembly instructions
  - Each logical step requires many machine instructions to execute
- Applications are executed as a series of instructions
  - The *execution path* of these instructions?
  - Thread
Every program has at least one thread

- Thread executes the body of the application
  - In Java, this is called the **main thread**
    - Begins executing statements starting with the first statement of the `main()` method
  - In Java every program has more than 1 thread
    - E.g., threads that do garbage collection, compile bytecodes into machine-level instructions, etc.
    - Programs are highly threaded
      - You may add additional application threads to this

Let's add another task to our program

- Say, computing the square-root of a number
- What if we wrote these as separate threads?
  - JVM has two distinct lists of instructions to execute
- Threads can be thought of as *tasks that we execute at roughly the same time*
- But in that case, why not just write multiple applications?
Threads that run within the same application process

- **Share the memory space** of the process
  - Information sharing is seamless

- Two diverse applications within the same machine may not communicate so well
  - For e.g., mail client and music application

In a multi-process environment data is separated by default

- This is fine for **dissimilar programs**

- Not OK for certain types of programs; e.g., a network server sends stock quotes to clients
  - Discrete task: Sending quote to client
    - Could be done in a separate thread
  - Data sent to the clients is the same
    - No point having a separate server for each client and ...
    - Replicating data held by the network server
Threads and sharing

- Threads within a process can access and share any object on the heap.
  - Each thread has space for its own local variables (stack).
- A thread is a discrete task that operates on data shared with other threads.

Thread Abstraction

- A thread is a single execution sequence that represents a separately schedulable task.
  - Single execution sequence
    - Each thread executes sequence of instructions – assignments, conditionals, loops, procedures, etc. – just as the sequential programming model.
  - Separately schedulable task
    - The OS can run, suspend, or resume a thread at any time.
Thread creation

- Using the `Thread` class
- Using the `Runnable` interface
The Thread class

```java
package java.lang;

public class Thread implements Runnable {
    public Thread();
    public Thread(Runnable target);
    public Thread(ThreadGroup group, Runnable target);
    public Thread(String name);
    public Thread(ThreadGroup group, String name);
    public Thread(Runnable target, String name);
    public Thread(ThreadGroup group, Runnable target, String name);
    public Thread(ThreadGroup group, Runnable target, String name, long stackSize);
    public void start();
    public void run();
}
```

Threads require 4 pieces of information

- **Thread name**
  - Default is Thread-N; N is a unique number

- **Runnable target**
  - List of instructions that the thread executes
  - Default: run() method of the thread itself

- **Thread group**
  - A thread is assigned to the thread group of the thread that calls the constructor

- **Stack size**
  - Store temporary variables during method execution
  - Platform-dependent: range of legal values, optimal value, etc.
A simple thread

```java
public class RandomGen extends Thread {
    private Random random;
    private int nextNumber;
    public RandomGen() {random = new Random();}

    public void run() {
        for (;;) {
            nextNumber = random.nextInt();
            try {
                } catch (InterruptedException ie) {
                    ... return;
                }
        }
    }
```

About the code snippet

- Extends the Thread class
- Actual instructions we want to execute is in the `run()` method
  - Standard method of the Thread class
    - Place where Thread begins execution
Contrasting the run() and main() methods

- main() method
  - This is where the first thread starts executing
  - The main thread

- The run() method
  - Subsequent threads start executing with this method

The contents of this slide-set are based on the following references