CONCURRENCY IN JAVA

Course “Parallel Computing”

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Java on a NUMA Architecture

- Loading Java 21 (default is Java 6):
  zusie> module avail
  ...
  zusie> module load jdk/21.0.2
  Module for jdk 21.0.2 loaded.
  zusie> java
  Picked up _JAVA_OPTIONS: -XX:+UseParallelGC -XX:ParallelGCThreads=4
  ...

- Advanced Runtime Options:
  -XX:+UseParallelGC
    Enables the use of the parallel scavenger garbage collector
    (also known as the throughput collector) to improve the performance
    of your application by leveraging multiple processors. ...
  -XX:ParallelGCThreads=N
    Sets the number of threads used for parallel garbage collection in
    the young and old generations. ...
  -XX:+UseNUMA
    Enables performance optimization of an application on a machine
    with nonuniform memory architecture (NUMA) by increasing the
    application’s use of lower latency memory. ...

Additional threads are created for garbage collection.
Java on a NUMA Architecture

- Pinning threads to cores:
  zusie> man 1 dplace

  ... Dplace is used to bind a related set of processes to specific cpus or nodes to prevent process migrations. In some cases, this will improve performance since a higher percentage of memory accesses will be to the local node.

  ... OPTIONS

  -c Cpu numbers. Specified as a list of cpus, optionally strided cpu ranges, or a striding pattern. Example: "-c 1", "-c 2-4", "-c 1,4-8,3", "-c 2-8:3", ...

  ... In some cases, version 2 of numatools will give better performance than version 1. ... In version 2, this memory is usually allocated local to the task’s node.
  ...

- Pin Java threads to physical cores in current CPU set:
  zusie> dplace -c 16-31 java ... // all threads on second blade
Java on a NUMA Architecture

- Control NUMA policy for processes or shared memory:
  zusie> man 1 numactl
  ...
  numactl runs processes with a specific NUMA scheduling or memory placement policy. ...
  ...
  OPTIONS
  -physcpubind=cpus, -C cpus
    Only execute process on cpus. ... Physical cpus may be specified as N,N,N or N-N or N,N-N or N-N,N-N and so forth. Relative cpus may be specified as +N,N,N or +N-N or +N,N-N and so forth. The + indicates that the cpu numbers are relative to the process’ set of allowed cpus in its current cpuset. ...
  ...

- Place Java threads on physical cores in current CPU set:
  zusie> numactl -C +16-31 java ... // all threads on second blade

- No pinning: threads may migrate among cores.
## Java on a NUMA Architecture

```
top -H -u login: press f j <ENTER>
```

```
top - 08:17:23 up 8 days, 17:01, 12 users, load average: 2.34, 0.53, 0.18
Tasks: 16842 total, 1 running, 16840 sleeping, 1 stopped, 0 zombie
Cpu(s): 0.8%us, 0.0%sy, 0.0%ni, 99.2%id, 0.0%wa, 0.0%hi, 0.0%si, 0.0%st
Mem: 2051061M total, 1958678M used, 92382M free, 0M buffers
Swap: 262143M total, 0M used, 262143M free, 1952269M cached
```

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<th>VIRT</th>
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<td>java</td>
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</table>

Column “P”: the core executing the thread.
public class HelloRunnable implements Runnable {
    public void run() {
        System.out.println("Hello!" acompanhado de uma nova linha);
    }
}

public static void main(String[] args) {
    Thread t = new Thread(new HelloRunnable());
    t.start();
    try { t.join() }
    catch (InterruptedException e) { }
}

public class HelloThread extends Thread {
    public void run() {
        System.out.println("Hello!" acompanhado de uma nova linha);
    }
}

public static void main(String[] args) {
    Thread t = new HelloThread();
    t.start();
    try { t.join() }
    catch (InterruptedException e) { }
}

Creating threads and waiting for their termination.
public class MatMultThreads {

    private static int N;
    private static int T;
    private static double[][] A;
    private static double[][] B;
    private static double[][] C;

    private static final class MultThread
        extends Thread {
        private int begin; private int end;
        public MultThread(int begin, int end) {
            this.begin = begin; this.end = end;
        }
        public void run() {
            for (int i = begin; i < end; i++) {
                for (int j = 0; j < N; j++) {
                    C[i][j] = 0;
                    for (int k = 0; k < N; k++)
                        C[i][j] += A[i][k]*B[k][j];
                }
            }
        }
    }

    private static void multiply() {
        int n = N/T;
        Thread[] thread = new MultThread[T];
        for (int i = 0; i < T; i++) {
            thread[i] = new MultThread(i*n, Math.min((i+1)*n,N));
            thread[i].start();
        }
        try {
            for (int i = 0; i < T; i++)
                thread[i].join();
        } catch(InterruptedException e) { }
    }

    private static void multiply2() {
        int n = N/T;
        Thread[] thread = new MultThread[T];
        for (int i = 0; i < T; i++) {
            thread[i] = new MultThread(i*n, Math.min((i+1)*n,N));
            thread[i].start();
        }
        try {
            for (int i = 0; i < T; i++)
                thread[i].join();
        } catch(InterruptedException e) { }
    }

    public static void main(String[] args) {
        try {
            N = Integer.parseInt(args[0]);
            T = Integer.parseInt(args[1]);
        }
        catch(NumberFormatException e) { return; }
        A = new double[N][N];
        B = new double[N][N];
        C = new double[N][N];
        multiply();
    }
}
Synchronization of Threads

- Synchronized methods:
  
  ```java
  public class SynchronizedCounter {
      private int c = 0;
      public synchronized void increment() { c++; }
      public synchronized int value() { return c; }
  }
  ```

- Synchronized statements:
  
  ```java
  public static void push(List<String> list, String name) {
      synchronized(list) { list.add(name); }
  }
  public static void pop(List<String> list) {
      synchronized(list) { list.remove(list.size()-1); }
  }
  ```

The executions of two synchronized methods/statements on the same lock object do not overlap.
Example: Dynamic Task Scheduling

```java
public class MatMultWorkers {

    private static int N;
    private static int T;
    private static double[][] A;
    private static double[][] B;
    private static double[][] C;
    private static int rows;

    private static final class MultWorker
        extends Thread {
            public void run() {
                while (true) {
                    int i;
                    synchronized (C) {
                        i = rows;
                        rows++;
                    }
                    if (i >= N) return;
                    for (int j = 0; j < N; j++) {
                        C[i][j] = 0;
                        for (int k = 0; k < N; k++)
                            C[i][j] += A[i][k]*B[k][j];
                    }
                }
            }
        }

    public static void multiply() {
        int n = N/T;
        Thread[] thread = new MultWorker[T];
        for (int i = 0; i < T; i++)
            thread[i] = new MultWorker();
        for (int i = 0; i < T; i++)
            thread[i].start();
        try {
            for (int i = 0; i < T; i++)
                thread[i].join();
        } catch(InterruptedException e) { }
    }

    public static void main(String[] args) {
        ... try {
            N = Integer.parseInt(args[0]);
            T = Integer.parseInt(args[1]);
        } catch(NumberFormatException e) { return; }
        A = new double[N][N];
        B = new double[N][N];
        C = new double[N][N];
        rows = 0;
        multiply();
    }
}
```
Memory Consistency Properties

Be careful: the effect of a write action by one thread is only guaranteed to be seen by the read action of another thread, if the actions are in the (transitive) happens-before relationship:

- Each action in a thread happens-before every later action (in program order) in the same thread.
- A synchronized method or statement exit happens-before every subsequent synchronized entry on the same lock object.
- A write to a volatile field happens-before every read to the same field.
- The start of a thread happens-before all actions of the thread.
- All actions of a thread happen-before every join of the thread.

The constructs synchronized, volatile, start and join define the happens-before relationship of a program.
The High-Level Concurrency API

Package `java.util.concurrent`.

- Lock objects
  - Package `java.util.concurrent.locks`
- Executors
  - Executor interfaces, thread pools, the Fork/Join framework.
- Concurrent collections
  - Interfaces `BlockingQueue`, `ConcurrentMap`, `ConcurrentNavigableMap`.
- Atomic variables
  - Package `java.util.concurrent.atomic`
- Pseudorandom numbers from multiple threads.
  - Class `ThreadLocalRandom`

We will investigate the “executors” in more detail.
Executors

- Core idea: separate “tasks” from “threads”.
  - Tasks: computations to be performed.
  - Threads: the unit of execution mapped to a processor core.

- Executors: an object that executes tasks.
  - Receives tasks and schedules them on a pool of threads.

- Tasks may or may not return a result:
  - `interface Executor`:
    - `void execute(Runnable command)`
    - `interface Runnable { void run(); }`
  - `interface ExecutorService`:
    - `<T> Future<T> submit(Callable<T> task)`
    - `Future<?> submit(Runnable task)`
    - `interface Callable<T> { T call(); ... }`
    - `interface Future<T> { T get(); ... }`
Thread Pools

- **Factory methods of class Executors**:  
  - `static ExecutorService newFixedThreadPool(int nThreads)`  
    Creates a thread pool that reuses a fixed number of threads operating off a shared unbounded queue.
  - `static ExecutorService newSingleThreadExecutor()`  
    Creates an Executor that uses a single worker thread operating off an unbounded queue.
  - `static ExecutorService newWorkStealingPool(int parallelism)`  
    Creates a thread pool that maintains enough threads to support given parallelism level, and may use multiple queues to reduce contention.

- **Manual creation of a ThreadPoolExecutor**:  
  - `ThreadPoolExecutor(int corePoolSize, int maximumPoolSize,  
    long keepAliveTime, TimeUnit unit,  
    BlockingQueue<Runnable> workQueue)`  
    Creates a new ThreadPoolExecutor with the given initial parameters and default thread factory and rejected execution handler.

Creation may be also parameterized by a “thread factory”.
Example: Tasks without Results

import java.util.*;
import java.util.concurrent.*;

public class MatMultPool {

    private static int N;
    private static int T;
    private static double[][] A;
    private static double[][] B;
    private static double[][] C;

    private static final class MultTask
        implements Runnable {
        private int i;
        public MultTask(int i) {
            this.i = i;
        }
        public void run() {
            for (int j = 0; j < N; j++) {
                C[i][j] = 0;
                for (int k = 0; k < N; k++)
                    C[i][j] += A[i][k]*B[k][j];
            }
        }
    }

    private static void multiply() {
        ExecutorService pool =
            Executors.newFixedThreadPool(T);
        Vector<Future<?>> result =
            new Vector<Future<?>> > (N);
        for (int i = 0; i < N; i++)
            result.add(pool.submit(new MultTask(i)));
        try {
            for (int i = 0; i < N; i++)
                result.get(i).get();
        }
        catch (InterruptedException e) { }
        catch (ExecutionException e) { }
        pool.shutdown();
    }

    public static void main(String[] args) {
        ...
        try {
            N = Integer.parseInt(args[0]);
            T = Integer.parseInt(args[1]);
        }
        catch(NumberFormatException e) { return; }
        A = new double[N][N];
        B = new double[N][N];
        C = new double[N][N];
        multiply();
    }
}
Example: Tasks with Results

```java
import java.util.*;
import java.util.concurrent.*;

public class MatMultFuture {

    private static int N;
    private static int T;
    private static double[][] A;
    private static double[][] B;
    private static double[][] C;

    private static final class MultResult
        implements Callable<double[]> {
        private int i;
        public MultResult(int i) {
            this.i = i;
        }
        public double[] call() throws Exception {
            double[] C = new double[N];
            for (int j = 0; j < N; j++) {
                C[j] = 0;
                for (int k = 0; k < N; k++)
                    C[j] += A[i][k]*B[k][j];
            }
            return C;
        }
    }

    private static void multiply() {
        ExecutorService pool = Executors.newFixedThreadPool(T);
        Vector<Future<double[]>> result = new Vector<Future<double[]>>(N);
        for (int i = 0; i < N; i++)
            result.add(pool.submit(new MultResult(i)));
        try {
            for (int i = 0; i < N; i++)
                C[i] = result.get(i).get();
        }
        catch(InterruptedException e) { }
        catch(ExecutionException e) { }
        pool.shutdown();
    }

    public static void main(String[] args) {
        ...
        try {
            N = Integer.parseInt(args[0]);
            T = Integer.parseInt(args[1]);
        }
        catch(NumberFormatException e) { return; }
        A = new double[N][N];
        B = new double[N][N];
        C = new double[N][];
        multiply();
    }
}
```

14/20
The Fork/Join Framework

A framework for recursive tasks.

- **Class** `ForkJoinPool`
  
  `ForkJoinPool(int parallelism)`
  
  `<T> ForkJoinTask<T> submit(ForkJoinTask<T> task)`

- **Abstract class** `ForkJoinTask<T>`:
  
  `ForkJoinTask<T> fork()`
  
  `public final T join()`
  
  `static void invokeAll(ForkJoinTask<?>... tasks)`

  - **Abstract subclass** `RecursiveAction`:
    
    `protected abstract void compute()`

  - **Abstract subclass** `RecursiveTask<T>`:
    
    `protected abstract T compute()`

Applies *work stealing*: when one thread runs out of tasks, it steals tasks created by another thread.
import java.util.*;
import java.util.concurrent.*;
public class MatMultRec {
    private static int N;
    private static int T;
    private static double[][] A;
    private static double[][] B;
    private static double[][] C;
    private static final class MultRec
        extends RecursiveAction {
        private int begin; private int end;
        public MultRec(int begin, int end) {
            this.begin = begin; this.end = end;
        }
        public void compute() {
            if (begin == end-1) {
                int i = begin;
                for (int j = 0; j < N; j++) {
                    C[i][j] = 0;
                    for (int k = 0; k < N; k++)
                        C[i][j] += A[i][k]*B[k][j];
                }
            }
            else if (begin < end) {
                int mid = (begin+end)/2;
                invokeAll(new MultRec(begin, mid), new MultRec(mid, end));
            }
        }
    }
    private static void multiply() {
        ForkJoinPool pool = new ForkJoinPool(T);
        ForkJoinTask<Void> task =
            pool.submit(new MultRec(0,N));
        task.join();
        pool.shutdown();
    }
    public static void main(String[] args) {
        ... try {
            N = Integer.parseInt(args[0]);
            T = Integer.parseInt(args[1]);
        }
        catch(NumberFormatException e) { return; }
        A = new double[N][N];
        B = new double[N][N];
        C = new double[N][N];
        multiply();
    }
}
Java 21: Virtual Threads

Light-weight threads assigned by JVM to a pool of OS threads.

// may also run "java -Djdk.virtualThreadScheduler.maxPoolSize=16"
System.setProperty("jdk.virtualThreadScheduler.maxPoolSize", "16");

// direct creation of virtual threads
Runnable task = () -> { System.out.println("running"); }; Thread thread = Thread.startVirtualThread(task);
thread.join(); System.out.println("Thread terminated");

// executor creates a virtual thread for every task submitted to the pool
ExecutorService executor = Executors.newVirtualThreadPerTaskExecutor(); Future<?> future = executor.submit(task);
future.get(); System.out.println("Task completed");

Whenever a virtual thread is blocked, it releases its OS thread to which the JVM then assigns another virtual thread (main purpose are high-throughput concurrent applications).
Distributed Memory Programming

- Use networking API for “message passing” programming.
  - TCP-based sockets for transferring streams of bytes.
- On a remote node a server process has to be started.
  - For instance, by “secure shell”.
  - Process waits on some port for connection requests.
  - By accepting a request, server receives socket to client.
- Client processes may request connections to the server.
  - Server identified by IP address and port number.
  - Upon acceptance, client receives socket to server.
- Sockets provide conventional input/output streams.
  - Standard I/O operations may be used for communication.
  - Output has to be (explicitly/automatically) flushed.

Low-level approach; there also exist high level alternatives, e.g., Java Remote Method Invocation (RMI).
Example: A Client/Server Program

import java.io.*;
import java.net.*;

public class MatMultNet {

    private final static String URL = "localhost";
    private final static int port = 9999;
    private static int N;
    private static int T;
    private static double[][] A;
    private static double[][] B;
    private static double[][] C;

    private static final class MultThread extends Thread {
        private int begin; private int end;
        public MultThread(int begin, int end) {
            this.begin = begin; this.end = end;
        }
        public void run() {
            for (int i = begin; i < end; i++) {
                for (int j = 0; j < N; j++) {
                    C[i][j] = 0;
                    for (int k = 0; k < N; k++)
                        C[i][j] += A[i][k]*B[k][j];
                }
            }
        }
    }

    private static void multiply() {
        int n = N/T;
        Thread[] thread = new MultThread[T];
        for (int i = 0; i < T; i++) {
            thread[i] = new MultThread(i*n, Math.min((i+1)*n,N));
            thread[i].start();
        }
        try {
            for (int i = 0; i < T; i++)
                thread[i].join();
        } catch(InterruptedException e) { }
    }

    public static void main(String[] args) {
        ... 
        if (args[0].equals("-client"))
            client();
        else
            server();
    }
}
Example: A Client/Server Program

```java
public static void server() {
    try {
        ServerSocket server = new ServerSocket(port);
        while (true) {
            Socket socket = server.accept();
            BufferedReader in =
                new BufferedReader(new InputStreamReader
                    (socket.getInputStream()));
            PrintWriter out =
                new PrintWriter(new OutputStreamWriter
                    (socket.getOutputStream()), true);
            String line = in.readLine();
            if (line == null) return;
            ...
            try {
                N = Integer.parseInt(args[0]);
                T = Integer.parseInt(args[1]);
            } catch (NumberFormatException e) { ... }
            A = new double[N][N];
            B = new double[N][N];
            C = new double[N][N];
            long t1 = System.currentTimeMillis();
            multiply();
            long t2 = System.currentTimeMillis();
            out.println((t2-t1) + " ms");
        }
    } catch (IOException e) { System.exit(-1); }
}

static void client() {
    try {
        BufferedReader console =
            new BufferedReader(new InputStreamReader
                (System.in));
        while (true) {
            String line = console.readLine();
            if (line == null) return;
            Socket socket = new Socket(URL, port);
            BufferedReader in =
                new BufferedReader(new InputStreamReader
                    (socket.getInputStream()));
            PrintWriter out =
                new PrintWriter(new OutputStreamWriter
                    (socket.getOutputStream()), true);
            out.println(line);
            String answer = in.readLine();
            if (answer == null) return;
            System.out.println(answer);
        }
    } catch (IOException e) { System.exit(-1); }
}
```