

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 scavenge 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
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	P	COMMAND
331708	k313270	20	0	62444	15m	1972	R	20	0.0	0:08.14	529	top
331467	k313270	20	0	106m	2536	1476	S	0	0.0	0:00.02	513	sshd
331468	k313270	20	0	55824	5704	2776	S	0	0.0	0:00.10	10	bash
331633	k313270	20	0	106m	2536	1476	S	0	0.0	0:00.02	513	sshd
331634	k313270	20	0	55824	5724	2796	S	0	0.0	0:00.10	580	bash
331709	k313270	20	0	32.8g	116m	12m	S	0	0.0	0:00.01	64	java
331710	k313270	20	0	32.8g	116m	12m	S	0	0.0	0:00.29	65	java
331711	k313270	20	0	32.8g	116m	12m	S	0	0.0	0:00.00	66	java
331712	k313270	20	0	32.8g	116m	12m	S	0	0.0	0:00.00	67	java
331713	k313270	20	0	32.8g	116m	12m	S	0	0.0	0:00.00	68	java
331714	k313270	20	0	32.8g	116m	12m	S	0	0.0	0:00.00	69	java
331715	k313270	20	0	32.8g	116m	12m	S	0	0.0	0:00.00	70	java

Column "P": the core executing the thread.

Multi-Threading in Java

```
public class HelloRunnable
    implements Runnable {
    public void run() {
        System.out.println("Hello!");
    }
}
```

```
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!");
    }
}
```

```
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.

Example: Matrix Multiplication

```
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) { }  
    }  
  
    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:

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

- Synchronized statements:

```
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

```
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 MultiWorker  
        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];  
                }  
            }  
        }  
    }  
}
```

```
private static void multiply() {  
    Thread[] thread = new MultiWorker[T];  
    for (int i = 0; i < T; i++)  
    {  
        thread[i] = new MultiWorker();  
        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

```
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][N];
    multiply();
}
```

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.

Example: Recursive Tasks

```
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.parallelism=16"  
System.setProperty("jdk.virtualThreadScheduler.parallelism", "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

```
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); }
}
```