Big Data Analytics

A. Parallel Computing / A.1 Threads

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Outline

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Processes and Threads

- **process**: a running program
  - each process has its exclusive memory
  - managed by the operating system, heavy weight
  - **distributed computing**: running on different machines

- **multitasking**: run several **processes** in parallel
  - OS switches between processes
  - **multiprocessing**: run in parallel on several processors

Processes and Threads

- **process**: a running program
  - each process has its exclusive memory
  - managed by the operating system, heavy weight
  - **distributed computing**: running on different machines
  - may have several threads
- **multitasking**: run several **processes** in parallel
  - OS switches between processes
  - **multiprocessing**: run in parallel on several processors
- **thread**: a running subprogram
  - threads can share memory (**shared address space**)
  - managed by the program, light weight
- **multithreading**: run several **threads** in parallel
  - may be switched between processors or run on several in parallel

Threads APIs

- POSIX threads (Pthreads; IEEE standard 1995): C
- C++ Standard library thread (2011): C++
- Java Standard library (1995, 2004): Java
  - Thread (java.lang; 1995)
  - Lock, ThreadPoolExecutor etc. (java.util.concurrent; 2004)
- Open Multi-Processing (OpenMP; 1997): C, C++, Fortran
  - Java ports: JOMP, omp4j

Outline

Starting Threads

Runnable:

- interface in java.lang
- only method: **void run()**.
- models a procedure that can be run.

Thread:

- class in java.lang
- constructor **Thread(Runnable)**: a thread to run a given Runnable.
- **Thread.start()**: begin to execute this thread.

Starting Threads / Example

```
public class HelloWorld3 implements Runnable {
    String msg;
    public HelloWorld3(String msg) {
        this.msg = msg;
    }
    public void run() {
        while (true)
            System.out.println(msg);
    }
    public static void main(String[] args) {
        new Thread(new HelloWorld3("A")).start();
        new Thread(new HelloWorld3("B")).start();
        new Thread(new HelloWorld3("C")).start();
        new Thread(new HelloWorld3("D")).start();
    }
}
```

Output

```
A
C
B
A
A
D
⋮
```

Interrupting Threads

- **Thread.interrupt()**:
  - set the thread's interrupted property to true.
  - if the thread is sleeping or waiting, an **InterruptedException** will be thrown.
- **Thread.interrupted()**:
  - get the value of the thread's interrupted property.
- **Thread.isAlive()**:
  - a thread is alive if it has been started, but not yet died.
- **Thread.currentThread()** (static):
  - get the thread executing the current code.
- **Thread.sleep(long)** (static):
  - the current thread sleeps for the given number of milliseconds.
- There is no way to stop a thread externally.
- There is no way to interrupt a thread that does not cooperate.

Interrupting Threads / Example / Example Computation

```
import java.util.*;

public class Primes {
    ArrayList<Long> primes = new ArrayList<>();

    public void compute(long max) {
        primes.add(2L);
        for (long n = 3; n < max; n = n+2) {
            boolean isPrime = true;
            for(Long prime: primes)
                if (n % prime == 0) {
                    isPrime = false;
                    break;
                }
            if (isPrime)
                primes.add(n);
        }
    }
}
```

Interrupting Threads / Example (non coop./broken)

```
import java.util.*;

public class Worker implements Runnable {
    public void run() {
        for (int i = 0; i < 1000; ++i) {
            System.out.println("Work step " + i);
            new Primes().compute(100000);
        }
    }

    public static void main(String[] args) {
        Thread worker = new Thread(new Worker());
        worker.start();
        while (worker.isAlive()) {
            String input = System.console().readLine();
            if (input.equals("interrupt")) {
                worker.interrupt();
                break;
            }
        }
    }
}
```

Output

```
Work step 0
Work step 1
Work step 2
interrupt
Work step 3
.
.
.
```

Interrupting Threads / Example (coop./fixed)

```java
import java.util.*;

public class Worker2 implements Runnable {
    public void run() {
        for (int i = 0; i < 1000; ++i) {
            if (Thread.currentThread().isInterrupted())
                break;
            System.out.println("Work step " + i);
            new Primes().compute(100000);
        }
    }

    public static void main(String[] args) {
        Thread worker = new Thread(new Worker2());
        worker.start();
        while (worker.isAlive()) {
            String input = System.console().readLine();
            if (input.equals("interrupt")) {
                worker.interrupt();
                break;
            }
        }
    }
}
```

Output

```
Work step 0
Work step 1
Work step 2
interrupt
```

Interrupting Threads / Example (sleeping)

```
import java.util.*;

public class Worker3 implements Runnable {
    public void run() {
        for (int i = 0; i < 1000; ++i) {
            System.out.println("Work step " + i);
            try {
                Thread.sleep(1000);
            } catch (InterruptedException ex) {
                break;
            }
        }
    }

    public static void main(String[] args) {
        Thread worker = new Thread(new Worker3());
        worker.start();
        while (worker.isAlive()) {
            String input = System.console().readLine();
            if (input.equals("interrupt")) {
                worker.interrupt();
                break;
            }
        }
    }
}
```

Outline

Synchronization

- Several threads running in parallel may need to exchange some information.
  - can be accomplished through shared variables

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- Several threads running in parallel may need to exchange some information.
  - can be accomplished through shared variables
- Several threads running in parallel may need to coordinate, e.g.,
  - a thread needs to wait until another is terminated
  - a thread requires exclusive access to some variable
    - e.g., to increment a counter or to edit an array
  - a thread requires some condition to hold to continue
    - e.g., further input in a stream being available

Synchronization

- Several threads running in parallel may need to exchange some information.
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  - a thread requires exclusive access to some variable
    - e.g., to increment a counter or to edit an array
  - a thread requires some condition to hold to continue
    - e.g., further input in a stream being available
- Called **synchronization**.

Waiting for Termination

- **Thread.join()**:
  - the current thread sleeps until the target thread dies.
- When a program is started, there exists one thread (often called main thread).
- a program terminates once all its threads died.

Waiting for Termination / Example

```
public class Counter {
    int count = 0;
    public void increment() { ++count; }
    public int value() { return count; }
}
```

```
public class ParallelCounters implements Runnable {
    Counter count;
    int num;

    public ParallelCounters(Counter count, int num) {
        this.count = count;
        this.num = num;
    }
    public void run() {
        for (int i = 0; i < num; ++i)
            count.increment();
    }

    public static void main(String[] args) throws InterruptedException {
        Counter count = new Counter();
        Thread a = new Thread(new ParallelCounters(count, 100));
        Thread b = new Thread(new ParallelCounters(count, 100));
        Thread c = new Thread(new ParallelCounters(count, 100));
        Thread d = new Thread(new ParallelCounters(count, 100));

        a.start(); b.start(); c.start(); d.start();

        System.out.println("counter: " + count.value());
    }
}
```

Waiting for Termination / Example

```
public class ParallelCounters2 implements Runnable {
    Counter count;
    int num;

    public ParallelCounters2 (Counter count, int num) {
        this.count = count;
        this.num = num;
    }
    public void run() {
        for (int i = 0; i < num; ++i)
            count.increment();
    }

    public static void main(String[] args) throws InterruptedException {
        Counter count = new Counter();
        Thread a = new Thread(new ParallelCounters2(count, 100));
        Thread b = new Thread(new ParallelCounters2(count, 100));
        Thread c = new Thread(new ParallelCounters2(count, 100));
        Thread d = new Thread(new ParallelCounters2(count, 100));

        a.start(); b.start(); c.start(); d.start();

        a.join(); b.join(); c.join(); d.join();

        System.out.println("counter: " + count.value());
    }
}
```

Synchronized Methods

- Even steps of very simple statements such as **++value** may be interleaved with steps in other threads and lead to corruption.
- For each object and class there exists an implicit lock (called monitor).
- Methods marked **synchronized**
  - try to acquire the monitor of their object and
  - block if the monitor is already taken by another thread until it becomes available.
  - thus, there is at most one thread executing any synchronized method at any time.
- **static synchronized** methods try to acquire the monitor of the class.
- The **synchronized(Object) { . . . }** statement tries to acquire the monitor of the given object/class.
- **Thread.holdsLock(Object)** (static) tests if the current thread holds a given monitor.

Synchronized Methods / Example

```
public class Counter2 {
    int count = 0;
    public synchronized void increment() { ++count; }
    public int value() { return count; }
}
```

```
public class ParallelCounters3 implements Runnable {
    Counter2 count;
    int num;

    public ParallelCounters3 (Counter2 count, int num) {
        this.count = count;
        this.num = num;
    }
    public void run() {
        for (int i = 0; i < num; ++i)
            count.increment();
    }

    public static void main(String[] args) throws InterruptedException {
        Counter2 count = new Counter2();
        Thread a = new Thread(new ParallelCounters3(count, 100));
        Thread b = new Thread(new ParallelCounters3(count, 100));
        Thread c = new Thread(new ParallelCounters3(count, 100));
        Thread d = new Thread(new ParallelCounters3(count, 100));

        a.start(); b.start(); c.start(); d.start();

        a.join(); b.join(); c.join(); d.join();

        System.out.println("counter: " + count.value());
```

Atomic Objects

- Atomic objects provide methods that are executed as a whole (and not interrupted by any other threads).
- **AtomicInteger** provides such operations for a simple int (**java.util.concurrent.atomic**):
  - **set(int)**: set a value.
  - **intValue()**: get.
  - **addAndGet(int)**: atomically adds a value.
  - **incrementAndGet()**: atomically increment.

Atomic Objects

```
import java.util.concurrent.atomic.AtomicInteger;

public class ParallelCounters4 implements Runnable {
    AtomicInteger count;
    int num;

    public ParallelCounters4(AtomicInteger count, int num) {
        this.count = count;
        this.num = num;
    }
    public void run() {
        for (int i = 0; i < num; ++i)
            count.incrementAndGet();
    }

    public static void main(String[] args) throws InterruptedException {
        AtomicInteger count = new AtomicInteger();
        Thread a = new Thread(new ParallelCounters4(count, 100));
        Thread b = new Thread(new ParallelCounters4(count, 100));
        Thread c = new Thread(new ParallelCounters4(count, 100));
        Thread d = new Thread(new ParallelCounters4(count, 100));

        a.start(); b.start(); c.start(); d.start();

        a.join(); b.join(); c.join(); d.join();

        System.out.println("counter: " + count.intValue());
    }
}
```

Synchronization Issues

- Deadlock:
  - Thread A is waiting for Thread B,
    Thread B is waiting for Thread A.
  - Thread A holds lock 1 and requests lock 2,
    Thread B holds lock 2 and requests lock 1.
  - The program freezes.

Synchronization Issues / Deadlock / Example

```
class Account {
    String id;
    double balance = 0;

    Account(String id) { this.id = id; }

    void withdraw(double amount) { balance -= amount; }
    void deposit(double amount) { balance += amount; }

    static void transfer(Account from, Account to, double amount) {
        synchronized(from) {
            synchronized(to) {
                from.withdraw(amount);
                to.deposit(amount);
            }
        }
    }
}
```

Synchronization Issues / Deadlock / Example (ctd.)

```
class ParallelTransactions implements Runnable {
    Account from, to;
    ParallelTransactions (Account from, Account to) {
        this.from = from;
        this.to = to;
    }
    public void run() {
        while (true) {
            Account.transfer(from, to, 100.00);
            System.out.println(" transfered 100.00 from " + from.id + " to " + to.id);
            try {
                Thread.sleep(1000);
            } catch (InterruptedException ex) {
                break;
            }
        }
    }
    public static void main(String[] args) {
        Account a = new Account("A"), b = new Account("B");
        new Thread(new ParallelTransactions(a, b)).start();
        new Thread(new ParallelTransactions(b, a)).start();
    }
}
```

Synchronization Issues / Deadlock / Example (fix)

```
class Account2 {
    String id;
    double balance = 0;

    Account2(String id) { this.id = id; }

    void withdraw(double amount) { balance -= amount; }
    void deposit(double amount) { balance += amount; }

    static synchronized void transfer(Account2 from, Account2 to, double amount) {
        synchronized(from) {
            synchronized(to) {
                from.withdraw(amount);
                to.deposit(amount);
            }
        }
    }
}
```

Conditions / Guarded Blocks

- Often threads require a specific condition to hold before they can resume their work.

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- **polling**:
  - repeatedly query the condition, proceed if it holds
  - wastes resources
  - possibly sleep between trials
    - sleep time not straight-forward to set

Conditions / Guarded Blocks

- Often threads require a specific condition to hold before they can resume their work.
- **polling**:
  - repeatedly query the condition, proceed if it holds
  - wastes resources
  - possibly sleep between trials
    - sleep time not straight-forward to set
- Condition:
  - a queue of threads to wait for a condition to become true
  - a method to wait on such a condition (**Object.wait**)
  - a method to signal that the condition may have changed (**Object.notifyAll**)
    - The condition itself is not part of the model.

Guarded Blocks / Example (1/2)

```
import java.util.*;
class Store {
    ArrayList<String> store = new ArrayList<>();
    synchronized void put(String item) { store.add(item); }
    synchronized String pop() { String item = store.get(0); store.remove(0); return item; }
}
```

```
class Producer implements Runnable {
    Store store;
    public Producer(Store store) { this.store = store; }
    public void run() {
        while (true) {
            try {
                Thread.sleep(Math.round(Math.random() * 1000));
            } catch (InterruptedException ex) {}
            String item = "A";
            store.put(item);
            System.out.println("produced " + item + ", store = " + store.store);
        }
    }
}
```

Guarded Blocks / Example (2/2)

```
class Consumer implements Runnable {
    Store store;
    public Consumer(Store store) { this.store = store; }
    public void run() {
        while (true) {
            if (store.store.size() >= 2) {
                String item1 = store.pop(), item2 = store.pop();
                System.out.println("consumed " + item1 + " and " + iten
                try {
                    Thread.sleep(Math.round(Math.random() * 1000));
                } catch (InterruptedException ex) {}
            }
        }
    }
}
```

```
class PCExample {
    public static void main(String[] args) {
        Store store = new Store();
        Producer prod = new Producer(store);
        Consumer cons = new Consumer(store);
        new Thread(prod).start();
        new Thread(cons).start();
    }
}
```

Output

```
produced A, store = [A]
produced A, store = [A, A]
produced A, store = [A, A, A]
produced A, store = [A, A, A, A]
produced A, store = [A, A, A, A, A]
.
.
.
```

Guarded Blocks / Example (fix; 1/2)

```
import java.util.*;
class Store {
    ArrayList<String> store = new ArrayList<>();
    public synchronized void put(String item) {
        synchronized(store) {
            store.add(item);
        }
        notifyAll();
    }
    public String pop() {
        String item;
        synchronized(store) {
            item = store.get(0);
            store.remove(0);
        }
        return item;
    }
    public String toString() {
        String s;
        synchronized(store) {
            s = store.toString();
        }
        return s;
    }
}
```

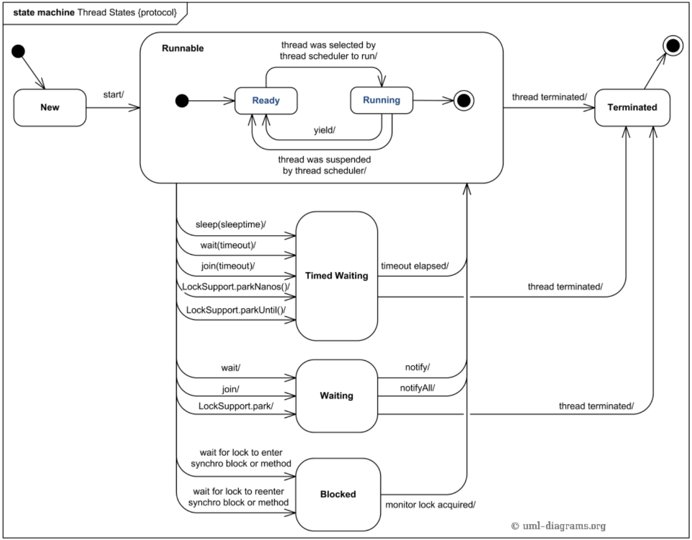
Guarded Blocks / Example (fix; 2/2)

```
class Consumer implements Runnable {
    Store store;
    public Consumer(Store store) { this.store = store; }
    public void run() {
        try {
            while (true) {
                if (store.store.size() >= 2) {
                    String item1 = store.pop(), item2 = store.pop();
                    System.out.println("consumed " + item1 + " and " +
                    Thread.sleep(Math.round(Math.random() * 1000));
                } else
                    synchronized(store) {
                        store.wait();
                    }
            }
        } catch (InterruptedException ex) {}
    }
}
```

Output

```
produced A, store = [A]
produced A, store = [A, A]
consumed A and A, store = []
produced A, store = [A]
produced A, store = [A, A]
consumed A and A, store = []
produced A, store = [A]
produced A, store = [A, A]
consumed A and A, store = []
produced A, store = [A]
```

Thread States



Information about threads at runtime

- **Thread.currentThread** (static): thread executing current code.
- **Thread.getState**: state of the thread.
- **Thread.getId**: get a numeric ID of the thread.
- **Thread.getActiveCount**: get number of concurrent threads.
- **Thread.enumerate**: get all concurrent threads.
- **Thread.getThreadGroup**: get group of the thread.

Outline

Locks

- A lock models mutually exclusive access to a resource.
  - only one thread can hold a lock at any time.
  - locks have methods to acquire and release them.
- **ReentrantLock**: reentrant implementation of interface **Lock**
  - reentrant: bookkeeping for repeated acquisitions and releases by the same thread.
- **Lock.lock**: acquire the lock, if possible, block otherwise until it becomes available.
- **Lock.unlock**: release the lock.
- **Lock.tryLock**: acquire the lock if possible, do nothing otherwise, return success.
  - atomic method for **Thread.holdsLock** followed by **synchronized**.
- in package **java.util.concurrent.locks**

Locks / Example

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

class Account3 {
    String id;
    double balance = 0;
    private final Lock lock = new ReentrantLock();

    Account3(String id) { this.id = id; }

    void withdraw(double amount) { balance -= amount; }
    void deposit(double amount) { balance += amount; }

    static boolean transfer(Account3 from, Account3 to, double amount) {
        boolean from_lock = from.lock.tryLock();
        boolean to_lock = to.lock.tryLock();
        if (from_lock && to_lock) {
            from.withdraw(amount);
            to.deposit(amount);
        }
        if (from_lock)
            from.lock.unlock();
        if (to_lock)
            to.lock.unlock();
        return from_lock && to_lock;
    }
}
```

Locks / Example

```
class ParallelTransactions3 implements Runnable {
    Account3 from, to;
     ParallelTransactions3 (Account3 from, Account3 to) {
        this.from = from;
        this.to = to;
    }
    public void run() {
        while (true) {
            while (! Account3.transfer(from, to, 100.00)) {
                System.out.println("accounts busy, delay somewhat");
                try {
                    Thread.sleep(1000);
                } catch (InterruptedException ex) {}
            }
            System.out.println(" transfered 100.00 from " + from.id + " t
            try {
                Thread.sleep(1000);
            } catch (InterruptedException ex) {}
        }
    }
    public static void main(String[] args) {
        Account3 a = new Account3("A"), b = new Account3("B");
        new Thread(new ParallelTransactions3(a, b)).start();
        new Thread(new ParallelTransactions3(b, a)).start();
    }
}
```

Output

```
transfered 100.00 from A to B
transfered 100.00 from B to A
transfered 100.00 from A to B
transfered 100.00 from B to A
transfered 100.00 from A to B
transfered 100.00 from B to A
accounts busy, delay somewhat
transfered 100.00 from A to B
transfered 100.00 from B to A
transfered 100.00 from A to B
accounts busy, delay somewhat
transfered 100.00 from B to A
```

Locks / Example

```java
class ParallelTransactions3 implements Runnable {
    Account3 from, to;
     ParallelTransactions3 (Account3 from, Account3 to) {
        this.from = from;
        this.to = to;
    }
    public void run() {
        while (true) {
            while (! Account3.transfer(from, to, 100.00)) {
                System.out.println("accounts busy, delay somewhat");
                try {
                    Thread.sleep(1000);
                } catch ( InterruptedException ex) {}
            }
            System.out.println(" transfered 100.00 from " + from.id + " t
            try {
                Thread.sleep(1000);
            } catch ( InterruptedException ex) {}
        }
    }
    public static void main(String[] args) {
        Account3 a = new Account3("A"), b = new Account3("B");
        new Thread(new ParallelTransactions3(a, b)).start();
        new Thread(new ParallelTransactions3(b, a)).start();
    }
}
```

Output

```
transfered 100.00 from A to B
transfered 100.00 from B to A
transfered 100.00 from A to B
transfered 100.00 from B to A
transfered 100.00 from A to B
transfered 100.00 from B to A
accounts busy, delay somewhat
transfered 100.00 from A to B
transfered 100.00 from B to A
transfered 100.00 from A to B
accounts busy, delay somewhat
transfered 100.00 from B to A
```

Locks / Good Practice

- if an exception is thrown after **Lock.lock**,
  in simple sequential code **Lock.unlock** may never be executed.

```
lck.lock();
...   // do something that may throw an exception
lck.unlock();
```

Locks / Good Practice

- if an exception is thrown after **Lock.lock**,
  in simple sequential code **Lock.unlock** may never be executed.

```
lck.lock();
... // do something that may throw an exception
lck.unlock();
```

- better wrap into a **try–finally** block:

```
try {
  lck.lock();
  ... // do something that may throw an exception
} finally {
  lck.unlock();
}
```

Outline

Thread pools

- Avoid creation and destruction of thread objects.
- Recycle thread objects, assigning Runnables to instances from a pool.

Thread pools

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- Recycle thread objects, assigning Runnables to instances from a pool.
- **ExecutorService** (interface):
  - **submit(Runnable)**: execute a runnable.
  - **shutdown**: wait for all submitted threads to complete.

Thread pools

- Avoid creation and destruction of thread objects.
- Recycle thread objects, assigning Runnables to instances from a pool.

- **ExecutorService** (interface):
  - **submit(Runnable)**: execute a runnable.
  - **shutdown**: wait for all submitted threads to complete.

- **Executors.newFixedThreadPool(int)** (static):
  - create an **ExecutorService** with a fixed number of threads
    - never run more than given number of threads in parallel.

Thread pools / Example

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

public class ExThreadpool implements Runnable {
    String name;
    public ExThreadpool(String name) { this.name = name; }

    public void run() {
        System.out.println("start " + name);
        try {
            Thread.sleep(1000);
        } catch (InterruptedException ex) {}
        System.out.println("end " + name);
    }

    public static void main(String[] args) {
        int cores = Runtime.getRuntime().availableProcessors();
        System.out.println("#cores = " + cores);

        ExecutorService pool = Executors.newFixedThreadPool(cores);
        for (int i = 0; i < 2*cores; ++i)
        pool.submit(new ExThreadpool("" + i));
            // pool.execute(new ExThreadpool("" + i));
        pool.shutdown();
    }
}
```

Output

```
cores = 4
start 0
start 1
start 2
start 3
end 0
end 1
start 4
start 5
end 2
start 6
end 3
start 7
end 4
end 5
end 6
end 7
```

Dependency Graphs

- computation composed of several atomic parts: **tasks**
- some tasks require the results of others as input
  $\rightsquigarrow$ dependency graph

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    - wait until the producing task is completed
    - then return the result
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  - like **Runnable**, but
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    - throw an **ExecutionException** if anything goes wrong
- abstract functions as interface: **Callable<T>**
  - like **Runnable**, but
  - returns a **Future<T>** – a function, not a procedure
  - may throw exceptions.
- **ExecutorService.submit(Callable<T>)**: execute a callable.

Dependency Graphs / Example

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

public class ExFuture2 {
    public static class Constant implements Callable<Double> {
        Double value;
        public Constant(Double value) { this.value = value; }
        public Double call() throws InterruptedException {
            System.out.println("Start computing constant");
            Thread.sleep(Math.round(value * 100));
            System.out.println("Compute constant " + value);
            return value;
        }
    }
    public static class Sum implements Callable<Double> {
        Future<Double> d1, d2;
        public Sum(Future<Double> d1, Future<Double> d2) {
            this.d1 = d1; this.d2 = d2;
        }
        public Double call() throws InterruptedException, ExecutionException {
            System.out.println("Start computing sum");
            Double v1 = d1.get(), v2 = d2.get();
            Thread.sleep(1000);
            System.out.println("Compute sum " + v1 + " + " + v2 + " = " + (v1+v2));
            return v1 + v2;
        }
    }
```

Dependency Graphs / Example

```java
    public static void main(String[] args) throws InterruptedException, ExecutionException {
        ExecutorService pool = Executors.newFixedThreadPool(8);
        Future<Double> c3_res = pool.submit(new Constant(3.0)),
            c5_res = pool.submit(new Constant(5.0)),
            c6_res = pool.submit(new Constant(6.0)),
            sum1_res = pool.submit(new Sum(c5_res, c6_res)),
            sum2_res = pool.submit(new Sum(c3_res, c5_res)),
            sum3_res = pool.submit(new Sum(sum1_res, sum2_res));
        System.out.println("(3+5)+(5+6) = " + sum3_res.get());
        pool.shutdown();
    }
}
```

Output

```
Start computing constant
Start computing constant
Start computing constant
Start computing sum
Start computing sum
Start computing sum
Compute constant 3.0
Compute constant 5.0
Compute constant 6.0
Compute sum 3.0 + 5.0 = 8.0
Compute sum 5.0 + 6.0 = 11.0
Compute sum 11.0 + 8.0 = 19.0
(3+5)+(5+6) = 19.0
```

Further Thread Classes

- concurrent collections:
  - provide atomic thread-safe query and edit operations for collections

Outline

Open MP

- Open Multi-Processing (OpenMP; 1997): C, C++, Fortran
  - Java ports:
    - JOMP: seems no longer available?
    - JAMP:
    - omp4j
- Multithreading directives are added as comments to the code.
  - starting with **omp**
- Special preprocessor **omp4j**:
  - Replace comments by code using the Java threads API.
  - Then compile the code using the standard compiler.

Parallel Sections / Example

```
public class HelloWorld {
    public static void main(String[] args) {
    // omp parallel threadNum(4)
    {
            System.out.print(" hello ");
        }
    }
}
```

Parallel Sections / Example

```
public class HelloWorld {
    public static void main(String[] args) {
    // omp parallel threadNum(4)
    {
        System.out.print("hello ");
      }
    }
}
```

Output

```
hello hello hello hello
```

Parallel Sections / Example / Under the Hood

```
public class HelloWorld {
    public static void main(String[] args) {
        class OMPContext {}
        final OMPContext ompContext = new OMPContext();
        final org.omp4j.runtime.IOMPExecutor ompExecutor = new org.omp4j.runtime.DynamicExecutor(4);

        for (int ompI = 0; ompI < 4; ompI++) {
            ompExecutor.execute(new Runnable(){
                @Override
                public void run() {
                    System.out.print("hello ");
                }
            });
        }
        ompExecutor.waitForExecution();
    }
}
```

Parallel For / Example

```
public class ExParallelFor {
    public static void main(String[] args) {
        // omp parallel for
        for (int i = 0; i < 10; i++) {
            System.out.print(i);
        }
    }
}
```

Parallel For / Example

```
public class ExParallelFor {
    public static void main(String[] args) {
        // omp parallel for
        for (int i = 0; i < 10; i++) {
            System.out.print(i);
        }
    }
}
```

Output

0213458679

Directives

Directives:

Directive	Usage	Behavior
// omp parallel	Before {...}	The statement will be invoked in parallel (as many threads as possible).
// omp parallel for	Before for-loop	The for-loop will be iterated in parallel.
// omp sections	Before {...}	Wrapper for // omp sections directives. It may not contain any other code
// omp section	Before {...}	The statement will be invoked together with other sections in parallel.
// omp critical	Before {...}	At most one thread will access the statement at any particular time.
// omp barrier	Before {}	All threads stop here until the for the last one.
// omp master	Before {...}	Only master thread will execute the statement.
// omp single	Before {...}	Only one thread will execute the statement, no matter which one.

Attributes:

Attribute	Behavior
threadNum(N)	The directive will be invoked with N threads. Default value is set to number of CPUs.
schedule(dynamic|static)	The directive will use dynamic or static executor. Default value is set to dynamic.
public(a,b)	Variables a and b are shared among all threads.
private(a,b)	Variables a and b are created (via parameter-less constructor) for each thread separately.
firstprivate(a,b)	Variables a and b are created (via copy-constructor) for each thread separately.

Outline

Primes / Sequential

```
import java.util.*;

public class Eratosthenes {
    boolean[] is_prime;
    public void compute(int max) {
        is_prime = new boolean[max+1];
        for (int i = 1; i <= max; ++i)
            is_prime[i] = true;
        for (int i = 2; i < Math.floor(Math.sqrt(max)); ++i) {
            if (is_prime[i]) {
                for (int j = 2*i; j <= max; j += i) {
                    is_prime[j] = false;
                }
            }
        }
    }
    public static void main(String[] args) {
        Eratosthenes primes = new Eratosthenes();
        primes.compute(1000000000);
    }
}
```

Primes / Bad Parallelization

```
import java.util.*;

public class Eratosthenes2 {
    boolean[] is_prime;
    public void compute(int max) {
        is_prime = new boolean[max+1];
        for (int i = 1; i <= max; ++i)
            is_prime[i] = true;
        for (int i = 2; i < Math.floor(Math.sqrt(max)); ++i) {
            if (is_prime[i]) {
                // omp parallel for
                for (int j = 2*i; j <= max; j += i) {
                    is_prime[j] = false;
                }
            }
        }
    }
    public static void main(String[] args) {
        Eratosthenes2 primes = new Eratosthenes2();
        primes.compute(1000000000);
    }
}
```

Primes / Recursive

```
import java.util.*;

public class Eratosthenes3 {
    boolean[] is_prime;

    public void compute(int max) {
        is_prime = new boolean[max+1];
        for (int i = 0; i < max+1; ++i)
            is_prime[i] = true;
        do_compute(max);
    }
    protected void do_compute(int max) {
        if (max <= 2)
            return;
        int max_factor = (int) Math.floor(Math.sqrt(max));
        do_compute(max_factor);
        for (int i = 2; i <= max_factor; ++i) {
            if (is_prime[i]) {
                for (int j = 2*i; j <= max; j += i) {
                    is_prime[j] = false;
                }
            }
        }
    }
    public static void main(String[] args) {
        Eratosthenes3 primes = new Eratosthenes3();
        primes.compute(1000000000);
    }
}
```

Primes / Good Parallelization

```
import java.util.*;

public class Eratosthenes4 {
    boolean[] is_prime;

    public void compute(int max) {
        is_prime = new boolean[max+1];
        for (int i = 0; i < max+1; ++i)
            is_prime[i] = true;
        do_compute(max);
    }
    protected void do_compute(int max) {
        if (max <= 2)
            return;
        int max_factor = (int) Math.floor(Math.sqrt(max));
        do_compute(max_factor);
        // omp parallel for
        for (int i = 2; i <= max_factor; ++i) {
            if (is_prime[i]) {
                for (int j = 2*i; j <= max; j += i) {
                    is_prime[j] = false;
                }
            }
        }
    }
    public static void main(String[] args) {
        Eratosthenes4 primes = new Eratosthenes4();
        primes.compute(1000000000);
    }
}
```

Primes / Good Parallelization

```
import java.util.*;

public class Eratosthenes4 {
    boolean[] is_prime;

    public void compute(int max) {
        is_prime = new boolean[max+1];
        for (int i = 0; i < max+1; ++i)
            is_prime[i] = true;
        do_compute(max);
    }
    protected void do_compute(int max) {
        if (max <= 2)
            return;
        int max_factor = (int) Math.floor(Math.sqrt(max));
        do_compute(max_factor);
        // omp parallel for
        for (int i = 2; i <= max_factor; ++i) {
            if (is_prime[i]) {
                for (int j = 2*i; j <= max; j += i) {
                    is_prime[j] = false;
                }
            }
        }
    }
    public static void main(String[] args) {
        Eratosthenes4 primes = new Eratosthenes4();
        primes.compute(1000000000);
    }
}
```

implementation	runtime [s]
sequential	10.4
badly parallel	>120.0
recursive	10.0
OK parallel	6.7
(using 8 cores)	

Matrix Multiplication / Sequential

```java
public class Matrix {
    int N, M;
    double[][] values;
    public Matrix(int N, int M) {
        this.N = N; this.M = M;
        values = new double[N][M];
    }
    public void fill_random() {
        for (int n = 0; n < N; ++n) {
            for (int m = 0; m < M; ++m) {
                values[n][m] = 2 * (Math.random() - 0.5);
            }
        }
    }

    public Matrix mul(Matrix B) throws IllegalArgumentException {
        if (M != B.N)
            throw new IllegalArgumentException("Number of columns and rows does not match in mul.");
        Matrix C = new Matrix(N, B.M);
        for (int n = 0; n < N; ++n) {
            for (int m = 0; m < B.M; ++m) {
                double val = 0;
                for (int k = 0; k < M; ++k) {
                    val += values[n][k] * B.values[k][m];
                }
                C.values[n][m] = val;
            }
        }
        return C;
    }
```

```java
    public static void main(String[] args) {
        Matrix A = new Matrix(1000, 2000),
            B = new Matrix(2000, 3000);
        A.fill_random();
        B.fill_random();
        Matrix C = A.mul(B);
    }
}
```

Matrix Multiplication / Parallelization

```
public class Matrix {
    int N, M;
    double[][] values;
    public Matrix(int N, int M) {
        this.N = N; this.M = M;
        values = new double[N][M];
    }
    public void fill_random() {
        for (int n = 0; n < N; ++n) {
            for (int m = 0; m < M; ++m) {
                values[n][m] = 2 * (Math.random() - 0.5);
            }
        }
    }

    public Matrix mul(Matrix B) throws IllegalArgumentException {
        if (M != B.N)
            throw new IllegalArgumentException("Number of columns and rows does not match in mul.");
        Matrix C = new Matrix(N, B.M);
        // omp parallel for
        for (int n = 0; n < N; ++n) {
            for (int m = 0; m < B.M; ++m) {
                double val = 0;
                for (int k = 0; k < M; ++k) {
                    val += values[n][k] * B.values[k][m];
                }
                C.values[n][m] = val;
            }
        }
        return C;
    }

    public static void main(String[] args) {
        Matrix A = new Matrix(1000, 2000),
            B = new Matrix(2000, 3000);
        A.fill_random();
        B.fill_random();
        Matrix C = A.mul(B);
    }
}
```

Matrix Multiplication / Tiled Sequential

```
public Matrix mul(Matrix B) throws IllegalArgumentException {
    if (M != B.N)
        throw new IllegalArgumentException("Number of columns and rows does not match in mul.");
    Matrix C = new Matrix(N, B.M);
    int T = (int) Math.ceil(Math.sqrt(M));
    for (int n0 = 0; n0 < N; n0+= T) {
        for (int m0 = 0; m0 < B.M; m0+= T) {
            for (int k0 = 0; k0 < M; k0+= T) {
                for (int n = n0; n < Math.min(N, n0+T); ++n) {
                    for (int m = m0; m < Math.min(M, m0+T); ++m) {
                        double val = 0;
                        for (int k = k0; k < Math.min(M, k0+T); ++k) {
                            val += values[n][k] * B.values[k][m];
                        }
                        C.values[n][m] += val;
                    }
                }
            }
        }
    }
    return C;
}
```

Matrix Multiplication / Tiled Sequential

```
public Matrix mul(Matrix B) throws IllegalArgumentException {
    if (M != B.N)
        throw new IllegalArgumentException("Number of columns and rows does not match in mul.");
    Matrix C = new Matrix(N, B.M);
    int T = (int) Math.ceil(Math.sqrt(M));
    for (int n0 = 0; n0 < N; n0+= T) {
        for (int m0 = 0; m0 < B.M; m0+= T) {
            for (int k0 = 0; k0 < M; k0+= T) {
                for (int n = n0; n < Math.min(N, n0+T); ++n) {
                    for (int m = m0; m < Math.min(M, m0+T); ++m) {
                        double val = 0;
                        for (int k = k0; k < Math.min(M, k0+T); ++k) {
                            val += values[n][k] * B.values[k][m];
                        }
                        C.values[n][m] += val;
                    }
                }
            }
        }
    }
    return C;
}
```

implementation	runtime [s]
sequential	21.2
parallel	4.5
tiled sequential	3.9
tiled parallel	1.2
(using 8 cores)	

Summary (1/2)

- **Threads** enable lightweight **concurrency**, i.e., concurrent execution of parts of a program (**tasks**).

- A **scheduler** assigns threads to processors/cores dynamically.
  - If there are more active threads as available processors/cores, the scheduler will do **time slicing**:
    - pick a ready thread and run it for a fixed amount of time,
    - suspend the active thread, then pick another one.
  - In consequence, there are no guarantees about execution order.

- Compared to **processes**,
  - threads have less overhead to setup and start,
  - threads **can share memory**,
  - threads communicate through shared memory (while processes communicate e.g., through pipes)

Summary (2/2)

- Threads require at least elementary synchronization such as
  - one thread waiting for the others to complete (**join**),
  - the possibility to **interrupt** another thread (cooperatively).

- When shared state is updated, more complex **synchronization** is required.
  - to avoid **data races**:
    - = concurrent update of the same variable, leaving it in an undefined state.
    - **atomic objects** offer a set of atomic operations.
    - **monitors** allow more fine-grained synchronization per object.
    - **guarded blocks** / **conditions** allow (possibly many) threads to wait until a condition holds and another thread to signal once this is the case.
    - **locks**/**mutexes** model exclusive access to a resource: only one thread at a time can acquire a lock, others have to wait, until it is released.

Further Readings

- General introduction to parallel computing: [Grama et al., 2003, ch. 1+2]

- Design of parallel algorithms: [Grama et al., 2003, ch. 3]

- Processes, threads and scheduling at operation system level: O'Gorman [2003]

References I

Ananth Grama, George Karypis, and Vipin Kumar. *Introduction to Parallel Computing*. Addison Wesley, 2003.

John O'Gorman. *The Linux Process Manager: The Internals of Scheduling, Interrupts and Signals*. John Wiley & Sons, Inc., New York, NY, USA, 2003. ISBN 0470847719.