

When: Thursday March 1, 9:00–10:15

Where: Stong College, room 203

What: all the material covered before the reading week

Please submit your project proposal (worth 3%) **before** Wednesday February 28.

Concurrency

EECS 4315

www.eecs.yorku.ca/course/4315/

- Brian Goetz, Tim Peierls, Joshua Bloch, Joseph Bowbeer, David Holmes and Doug Lea. *Java Concurrency in Practice*. Addison-Wesley, 2006.
- Mary Campione, Kathy Walrath and Alison Huml. *The Java Tutorial. Lesson: Threads: Doing Two or More Tasks At Once*.
- James Gosling, Bill Joy, Guy L. Steele Jr., Gilad Bracha and Alex Buckley. *The Java Language Specification*. 2015.

Threads can exchange information by accessing and updating shared attributes.

Question

One thread executes

```
v = 1;
```

```
v = v + 1;
```

and another thread executes

```
v = 0;
```

What is the final value of v?

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and another thread executes

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What is the final value of v?

Answer

0, 1 or 2. This example shows that concurrency gives rise to nondeterminism.

Question

One thread executes

```
v = v + 1;
```

and another thread executes

```
v = v + 1;
```

If the initial value of v is 0, then what is the final value of v ?

Question

One thread executes

```
v = v + 1;
```

and another thread executes

```
v = v + 1;
```

If the initial value of v is 0, then what is the final value of v ?

Answer

1 or 2.

Question

How can the final value of v be 1?

Question

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Answer

The assignment $v = v + 1$ is not atomic.

Question

How can the final value of v be 1?

Answer

The assignment $v = v + 1$ is not atomic.

0: `getstatic`

3: `iconst_1`

4: `iadd`

5: `putstatic`

Question

One thread executes

```
v = 0;
```

and another thread executes

```
v = Long.MAX_VALUE;
```

How many different final values can v have?

Question

One thread executes

```
v = 0;
```

and another thread executes

```
v = Long.MAX_VALUE;
```

How many different final values can v have?

Answer

4.

Question

How can v have 4 different final values?

Question

How can `v` have 4 different final values?

Answer

The assignments `v = 0` and `v = Long.MAX_VALUE` may not be atomic (on 32 bit machines).

Thread creation

In Java, threads are created dynamically:

```
// create and initialize Thread object
Thread thread = new Thread();
// execute run method of Thread object concurrently
thread.start();
```

The class `Thread` is part of package `java.lang` (and, hence, does not need to be imported). Its API can be found at the URL

<https://docs.oracle.com/javase/8/docs/api/java/lang/Thread.html> .

- `public Thread(String name)`
Initializes a new `Thread` object with the specified name as its name.
- `public void start()`
Causes this thread to begin execution; the Java virtual machine calls the `run` method of this thread.
- `public void run()`
This method does nothing and returns.

Question

Develop a Java class called `Printer` that is a `Thread` and prints its name 1000 times.

Two concurrent printers

Question

Develop an app that creates two `Printers` with names 1 and 2 and run them concurrently.

Two concurrent printers

Question

Develop an app that creates two `Printers` with names 1 and 2 and run them concurrently.

Question

What is the output of the app?

Two concurrent printers

Question

Develop an app that creates two **Printers** with names 1 and 2 and run them concurrently.

Question

What is the output of the app?

Answer

A sequence of 1000 1's and 2's (arbitrarily interleaved). This example shows that concurrency gives rise to nondeterminism.

Question

What happens if we replace `start` with `run` in the app?

Two concurrent printers

Question

What happens if we replace `start` with `run` in the app?

Answer

Lets try it.

Two concurrent printers

Question

What happens if we replace `start` with `run` in the app?

Answer

Lets try it.

Answer

The output is a sequence of 1000 1's followed by 1000 2's

Java only supports single inheritance

The following is **not** allowed in Java.

```
public class Printer extends Applet, Thread
```

Thread creation

```
// create and initialize Runnable object
Runnable runnable = new ...();
// create and initialize Thread object
Thread thread = new Thread(runnable);
// execute run method of Runnable object concurrently
thread.start();
```

The interface `Runnable` is part of package `java.lang` (and, hence, does not need to be imported). Its API can be found at the URL

<https://docs.oracle.com/javase/8/docs/api/java/lang/Runnable.html>

Runnable is an interface

In Java, you cannot create instances of an interface.

```
public class Printer implements Runnable {  
    ...  
}
```

The assignment

```
Runnable printer = new Printer();
```

is valid since the class `Printer` implements the interface `Runnable`.

Question

Develop a Java class called `Printer` that implements `Runnable` and prints the thread's name 1000 times.

How many different executions?

Question

One thread prints 1 one. Another thread prints 1 two. How many different executions are there?

How many different executions?

Question

One thread prints 1 one. Another thread prints 1 two. How many different executions are there?

Answer

2.

How many different executions?

Question

One thread prints 2 ones. Another thread prints 2 twos. How many different executions are there?

How many different executions?

Question

One thread prints 2 ones. Another thread prints 2 twos. How many different executions are there?

Answer

6.

How many different executions?

Question

One thread prints 3 ones. Another thread prints 3 twos. How many different executions are there?

How many different executions?

Question

One thread prints 3 ones. Another thread prints 3 twos. How many different executions are there?

Answer

20.

How many different executions?

Question

One thread prints 1000 ones. Another thread prints 1000 twos.
How many different executions are there?

How many different executions?

Question

One thread prints 1000 ones. Another thread prints 1000 twos.
How many different executions are there?

Answer

```
204815162698948971433516250298082504439642488798139
703382038263767174818620208375582893299418261020620
146476631999802369241548179800452479201804754976926
157856301289663432064714851152395251651227768588611
539546256147907378668464154444533617613770073855673
814589630071306510455959514479888746206368718514551
828551173166276253663773084682932255389049743859481
431755030783796444370810085163724827462791417016619
883764840843541430817785947037746565188475514680749
694674923803033101818723298009668567458560252549910
118113525353465888794196665367490451130611009631190
6270342502293155911108976733963991149120.
```

How many executions?

Question

One thread prints 1000 ones. Another thread prints 1000 twos.
How many different executions are there?

How many executions?

Question

One thread prints 1000 ones. Another thread prints 1000 twos.
How many different executions are there?

Answer

$$\binom{2000}{1000} = \frac{2000!}{1000!1000!}.$$

How many executions?

Question

One thread executes n instructions. Another thread executes n instructions. How many different executions are there?

How many executions?

Question

One thread executes n instructions. Another thread executes n instructions. How many different executions are there?

Answer

At most $\binom{2n}{n}$.

How many executions?

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Answer

At most $\binom{2n}{n}$.

Question

Can there be fewer?

How many executions?

Question

One thread executes n instructions. Another thread executes n instructions. How many different executions are there?

Answer

At most $\binom{2n}{n}$.

Question

Can there be fewer?

Answer

Yes. For example, if each instruction is $x = 1$ then there is only one execution.

How many executions?

Question

There are k threads. Each thread executes n instructions. How many different executions are there?

How many executions?

Answer

$$\binom{kn}{n} \binom{(k-1)n}{n} \dots \binom{2n}{n}$$

How many executions?

Answer

$$\binom{kn}{n} \binom{(k-1)n}{n} \cdots \binom{2n}{n}$$
$$= \frac{(kn)!}{n!((k-1)n)!} \frac{((k-1)n)!}{n!((k-2)n)!} \cdots \frac{(2n)!}{n!n!}$$

How many executions?

Answer

$$\begin{aligned} & \binom{kn}{n} \binom{(k-1)n}{n} \cdots \binom{2n}{n} \\ &= \frac{(kn)!}{n!((k-1)n)!} \frac{((k-1)n)!}{n!((k-2)n)!} \cdots \frac{(2n)!}{n!n!} \\ &= \frac{(kn)!}{(n!)^k} \end{aligned}$$

How many executions?

Answer

$$\begin{aligned} & \binom{kn}{n} \binom{(k-1)n}{n} \cdots \binom{2n}{n} \\ &= \frac{(kn)!}{n!((k-1)n)!} \frac{((k-1)n)!}{n!((k-2)n)!} \cdots \frac{(2n)!}{n!n!} \\ &= \frac{(kn)!}{(n!)^k} \\ &= \frac{(kn)(kn-1)\cdots(kn-n+1)}{n!} \cdots \frac{2n(2n-1)\cdots(n+1)}{n!} \frac{n!}{n!} \end{aligned}$$

How many executions?

Answer

$$\begin{aligned} & \binom{kn}{n} \binom{(k-1)n}{n} \cdots \binom{2n}{n} \\ &= \frac{(kn)!}{n!((k-1)n)!} \frac{((k-1)n)!}{n!((k-2)n)!} \cdots \frac{(2n)!}{n!n!} \\ &= \frac{(kn)!}{(n!)^k} \\ &= \frac{(kn)(kn-1)\cdots(kn-n+1)}{n!} \cdots \frac{2n(2n-1)\cdots(n+1)}{n!} \frac{n!}{n!} \\ &\geq \left(\frac{2n(2n-1)\cdots(n+1)}{n!} \right)^{k-1} \end{aligned}$$

How many executions?

Answer

$$\begin{aligned} & \binom{kn}{n} \binom{(k-1)n}{n} \cdots \binom{2n}{n} \\ &= \frac{(kn)!}{n!((k-1)n)!} \frac{((k-1)n)!}{n!((k-2)n)!} \cdots \frac{(2n)!}{n!n!} \\ &= \frac{(kn)!}{(n!)^k} \\ &= \frac{(kn)(kn-1)\cdots(kn-n+1)}{n!} \cdots \frac{2n(2n-1)\cdots(n+1)}{n!} \frac{n!}{n!} \\ &\geq \left(\frac{2n(2n-1)\cdots(n+1)}{n!} \right)^{k-1} \\ &= \left(\frac{2n(2n-1)\cdots(n+1)}{n(n-1)\cdots 2} \right)^{k-1} \end{aligned}$$

How many executions?

Answer

$$\begin{aligned} & \binom{kn}{n} \binom{(k-1)n}{n} \cdots \binom{2n}{n} \\ &= \frac{(kn)!}{n!((k-1)n)!} \frac{((k-1)n)!}{n!((k-2)n)!} \cdots \frac{(2n)!}{n!n!} \\ &= \frac{(kn)!}{(n!)^k} \\ &= \frac{(kn)(kn-1)\cdots(kn-n+1)}{n!} \cdots \frac{2n(2n-1)\cdots(n+1)}{n!} \frac{n!}{n!} \\ &\geq \left(\frac{2n(2n-1)\cdots(n+1)}{n!} \right)^{k-1} \\ &= \left(\frac{2n(2n-1)\cdots(n+1)}{n(n-1)\cdots 2} \right)^{k-1} \\ &\geq n^{k-1} \end{aligned}$$

How many executions?

Question

There are k threads. Each thread executes n instructions. How many different executions are there?

Answer

In the worst case, more than n^{k-1} .

Conclusion

The number of different executions may grow exponential in the number of threads.