Concurrency

EECS 4315

www.cse.yorku.ca/course/4315/

Books

- 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. and Gilad Bracha. The Java Language Specification. Third edition

Concurrency

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?

Concurrency

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Answer

0, 1 or 2.

Concurrency

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

Concurrency

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```

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

Answer

1 or 2.

Concurrency

Question

How can the final value of v be 1?

Concurrency

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Answer

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

Concurrency

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
```

Concurrency

Question

One thread executes

```
v = 0;
```

and another thread executes

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

How many different final values can v have?

Concurrency

Question

One thread executes

```
v = 0;
```

and another thread executes

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

How many different final values can v have?

Answer

4.

Concurrency

Question

How can v have 4 different final values?

Concurrency

Question

How can v have 4 different final values?

Answer

The assignments `v = 0` and `v = Long.MAX_VALUE` may not be atomic.

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`.

Thread API

- `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.

Printer

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 **`Printer`**s with names 1 and 2 and run them concurrently.

Two Concurrent Printers

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Question

What is the output of the app?

Two Concurrent Printers

Question

Develop an app that creates two `Printer`s 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.

Two Concurrent Printers

Question

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

Two Concurrent Printers

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

Answer

Let's try it.

Two Concurrent Printers

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

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Let’s 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 concurrent
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`.

Printer

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

20481516269894897143351625029808250443964248879813970338203826376717481862020837558289329941826102062014647663199980236924154817980045247920180475497692615785630128966343206471485115239525165122776858861153954625614790737866846415444453361761377007385567381458963007130651045595951447988874620636871851455182855117316627625366377308468293225538904974385948143175503078379644437081008516372482746279141701661988376484084354143081778594703774656518847551468074969467492380303310181872329800966856745856025254991011811352535346588879419666536749045113061100963119062703425022931559111089767339639911 49120.

How Many Different 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 Different Executions?

Question

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

How Many Different Executions?

Question

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

Answer

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

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Question

Can there be fewer?

How Many Different 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 Different Executions?

Question

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

How Many Different 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.

Conclusion

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

Java Code

```java
public static void main(String[] args)
{
  Printer one = new Printer("1");
  Printer two = new Printer("2");
  one.start();
  two.start();
}
```

Executions

Question

Draw the state-transition diagram.

Executions