States and Transitions

EECS 4315

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

Nondeterminism

Nondeterministic code is code that, even for the same input, can exhibit different behaviours on different runs, as opposed to deterministic code.

- Randomization and
- concurrency

both give rise to nondeterminism.

Limitations of testing of nondeterministic code include

- no guarantee that all different behaviours have been checked, and
- errors may be difficult to reproduce.

Alternatives to Testing

To detect bugs in nondeterministic code, testing needs to be supplemented with other approaches.

Question

How to tackle the limitations of testing of nondeterministic code?

Alternatives to Testing

To detect bugs in nondeterministic code, testing needs to be supplemented with other approaches.

Question

How to tackle the limitations of testing of nondeterministic code?

Answer

Control the nondeterminism: this allows us to

- systematically check all different behaviours and
- reproduce errors.

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

2048151626989489714335162502980825044396424887981397033820382637671748186202083755828932994182610206201464766319998023692415481798004524792018047549769261578563012896634320647148511523952516512277685886115395462561479073786684641544445336176137700738556738145896300713065104559595144798887462063687185145518285511731662762536637730846829322553890497438594814317550307837964443708100851637248274627914170166198837648408435414308177859470377465651884755146807496946749238030331018187232980096685674585602525499101181135253534658887941966653674904511306110096311906270342502293155911108976733963991149120.

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?

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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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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

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

How Many Different Executions?

Answer

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

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

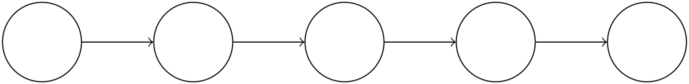
In the worst case, more than n^k.

Conclusion

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

Execution

An execution consists of states connected by transitions.



State

A state of a Java virtual machine (JVM) includes

- the heap,
- for each thread
  - its state (runnable, waiting, terminated, . . .),
  - its stack,
  - etc,
- etc.

https://docs.oracle.com/javase/8/docs/platform/jvmti/jvmti.html

Transition

A transition of a JVM takes the JVM from one state to another by executing a bytecode instruction.

Java Code

```
public class HelloWorld
{
  public static void main(String[] args)
  {
    System.out.println("Hello World");
  }
}
```

Java Bytecode

The command

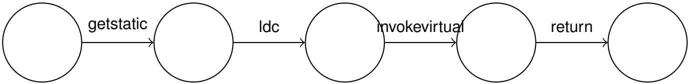
```
javap -c HelloWorld.class
```

produces

```
0: getstatic
// of attribute System.out
// of class PrintStream
3: ldc
// String "Hello World"
5: invokevirtual
// of method println
// with argument String
8: return
```

Java Code and Execution

```
public class HelloWorld
{
  public static void main(String[] args)
  {
    System.out.println("Hello World");
  }
}
```



Java Code

```
public class RedOrGreen
{
  public static void main(String[] args)
  {
    Random random = new Random();
    if (random.nextBoolean())
    {
      System.out.println("Red");
    }
    else
    {
      System.out.println("Green");
    }
  }
}
```

Java Bytecode

```
0: new
3: dup
4: invokespecial
7: astore_1
8: aload_1
9: invokevirtual
12: ifeq
15: getstatic
18: ldc
20: invokevirtual
23: goto
26: getstatic
29: ldc
31: invokevirtual
34: return
```

Executions

Question

Draw the state-transition diagram.

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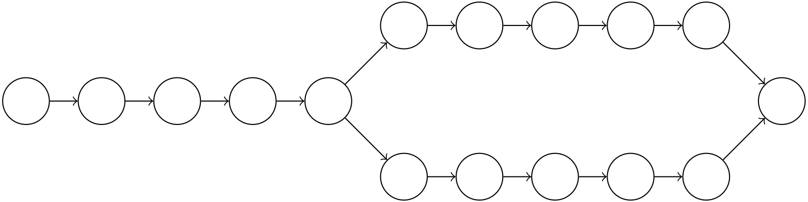


Java Code

```
public Printer(String name)
{
  super(name);
}
```

Java Bytecode

```
0: aload_0
1: aload_1
2: invokespecial
5: return
```

Java Code

```
public void run()
{
  final int NUMBER = 1000;
  for (int i = 0; i < NUMBER; i++)
  {
    System.out.print(this.getName());
  }
}
```

Java Bytecode

```
0: sipush
3: istore_1
4: iconst_0
5: istore_2
6: goto
9: getstatic
12: aload_0
13: invokevirtual
16: invokevirtual
19: iinc
22: iload_2
23: sipush
26: if_icmplt
29: return
```

Java Code

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

Java Bytecode

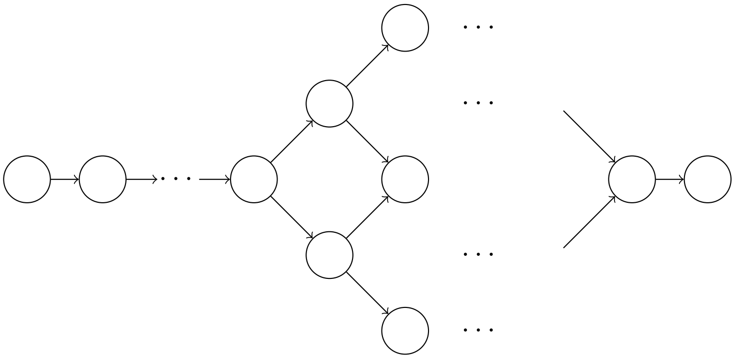
```
0: new
3: dup
4: ldc
6: invokespecial
9: astore_1
10: new
13: dup
14: ldc
16: invokespecial
19: astore_2
20: aload_1
21: invokevirtual
24: aload_2
25: invokevirtual
28: return
```

Executions

Question

Draw the state-transition diagram.

Executions



State Space Explosion Problem

Problem

The size of the state space, that is, the number of states, may grow exponentially in the number of threads.

State Space Explosion Problem

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The size of the state space, that is, the number of states, may grow exponentially in the number of threads.

This is one of the major challenges in model checking.

Model Checking

Develop a model (states connected by transitions) of the code and check properties of the model.