HOL6500 - Finding And Solving Java Deadlocks

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Javaspecialists.eu
java training

The Team

- Kirk Pepperdine (Java Performance Tuning)
- Jeff Genender (Apache Member, Savoir Technologies)
- Henri Tremblay (EasyMock lead developer, OCTO Technology architect)
- Ben Evans (Author, CEO jClarity)
- Dario Laverde (Java architect, lecturer, author)
- Nathan Reynolds (Exalogic Performance Architect)
- Martijn Verburg (CTO jClarity, Diabolical Developer)
- Heinz Kabutz (The Java Specialists' Newsletter)

How We Help Java

- **Support open source software**
- **Consult and train Java developers**
  - **We only do extreme courses**
- **Community leaders**
- **JCP members and spec leads**
- **Involved in OpenJDK**
- **Kirk, Jeff, Heinz are Java Champions**

Java™ Champions

1: Introduction

Structure Of Hands-On Lab

- Three short lectures, each followed by a short lab
  - https://github.com/kabutz/DeadlockLabJavaOne2012.git
- We only have two hours to cover a lot, so let's go!

Questions

- **Please please please please ask questions!**
- **Interrupt us at any time**
  - **This lab is on deadlocks, we need to keep focused in available time**
- **The only stupid questions are those you do not ask**
  - **Once you've asked them, they are not stupid anymore**
- **The more you ask, the more we all learn**

HOL6500 - Finding And Solving Java Deadlocks

Avoiding Liveness Hazards

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10: Avoiding Liveness Hazards

- **Fixing safety problems can cause liveness problems**
  - **Don't indiscriminately sprinkle "synchronized" into your code**
- **Liveness hazards can happen through**
  - **Lock-ordering deadlocks**
    - **Typically when you lock two locks in different orders**
    - **Requires global analysis to make sure your order is consistent**
      - **Lesson: only ever hold a single lock per thread!**
  - **Resource deadlocks**
    - **This can happen with bounded queues or similar mechanisms meant to bound resource consumption**
- **A thread deadlocked in BLOCKED state can never recover**

Lab 1: Deadlock Resolution By Global Ordering

Avoiding Liveness Hazards

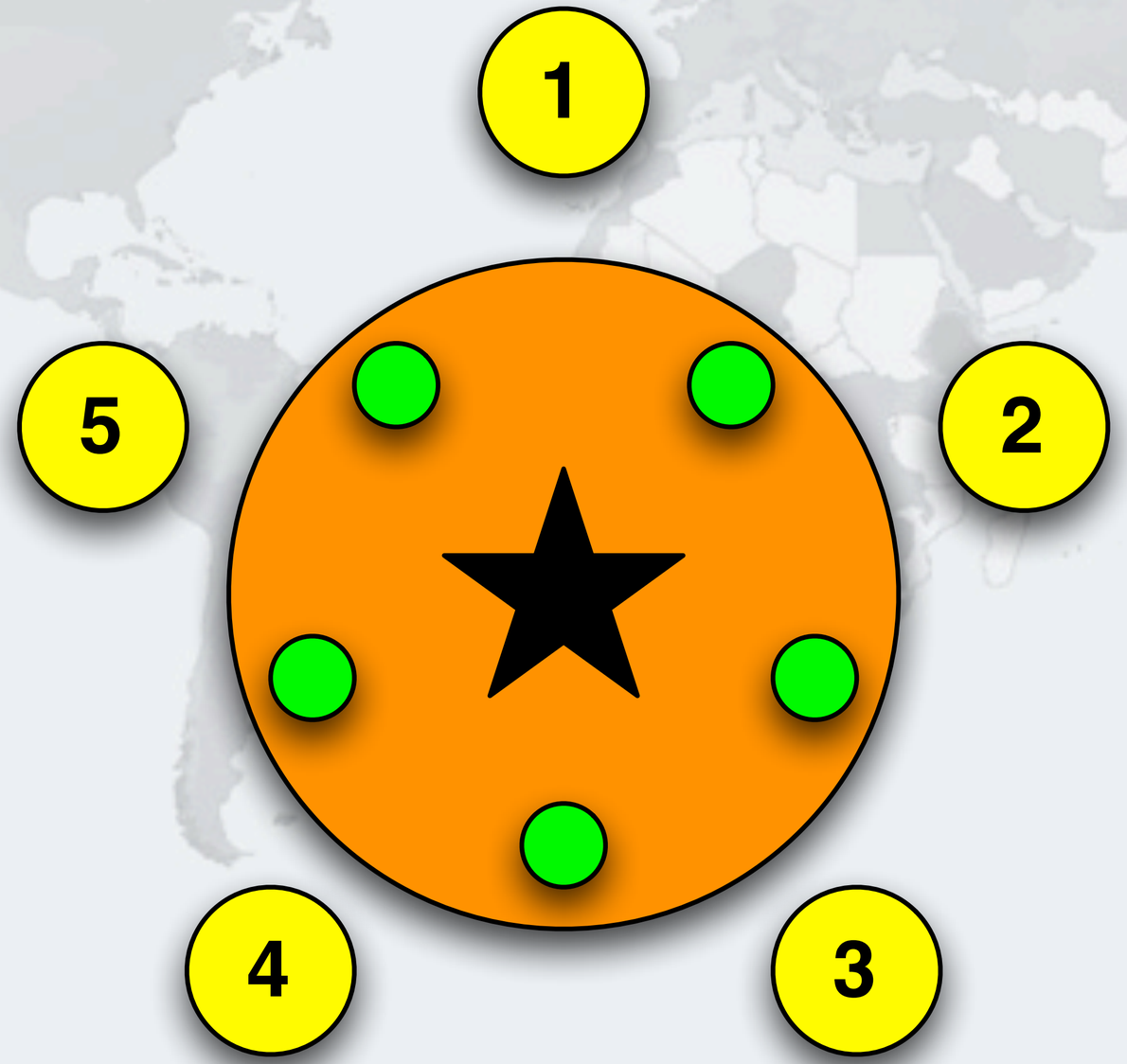
Lab 1: Deadlock Resolution By Global Ordering

- **Classic problem is that of the "dining philosophers"**
  - **We changed that to the "drinking philosophers"**
    - **That is where the word "symposium" comes from**
      - **sym - together, such as "symphony"**
      - **poto - drink**
    - **Ancient Greek philosophers used to get together to drink & think**
- **In our example, a philosopher needs two glasses to drink**
  - **First he takes the right one, then the left one**
  - **When he finishes drinking, he returns them and carries on thinking**

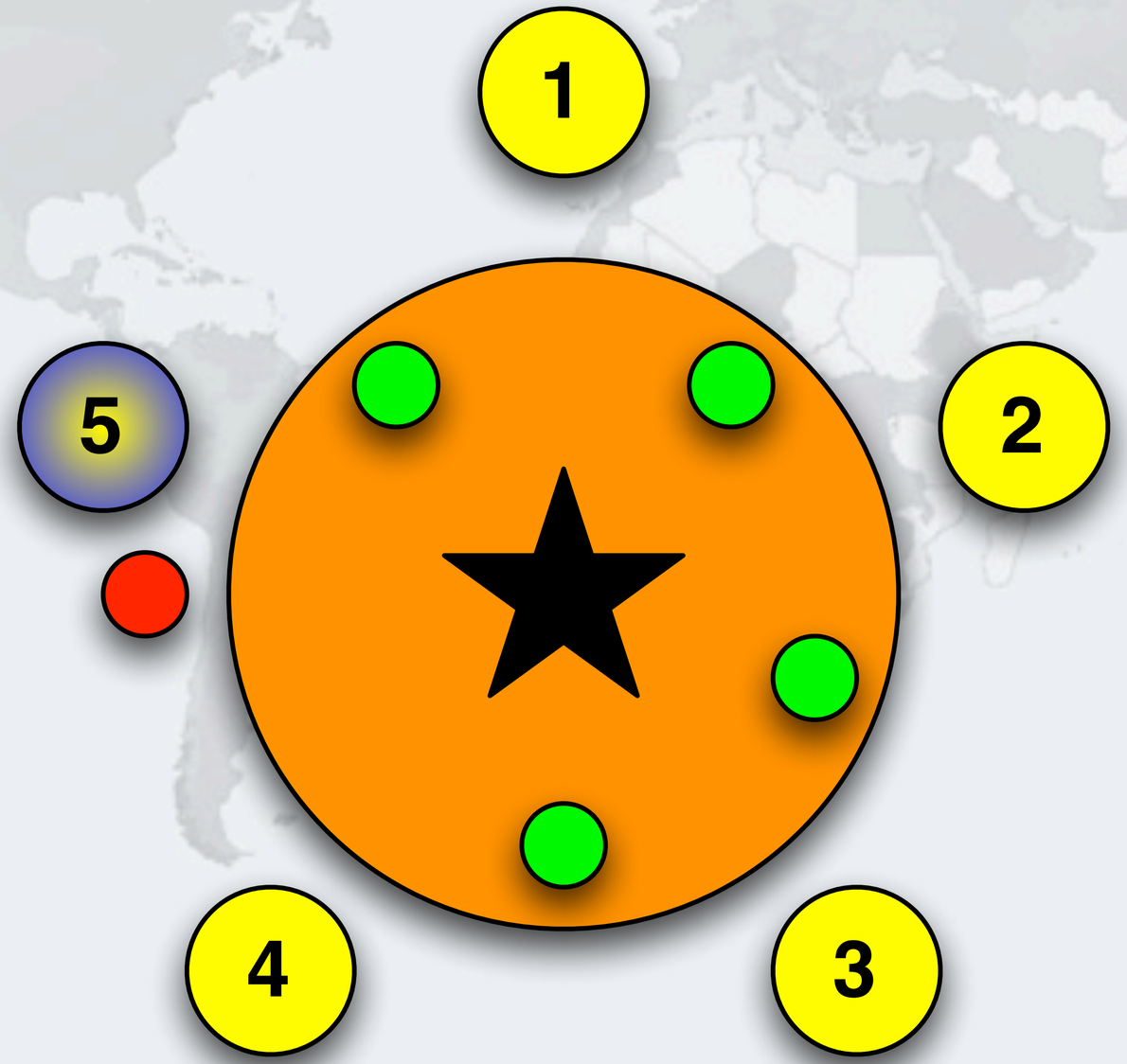
Drinking Philosophers In Limbo

- **The standard rule is that every philosopher first picks up the right cup, then the left**
  - **If all of the philosophers want to drink and they all pick up the right cup, then they all are holding one cup but cannot get the left cup**

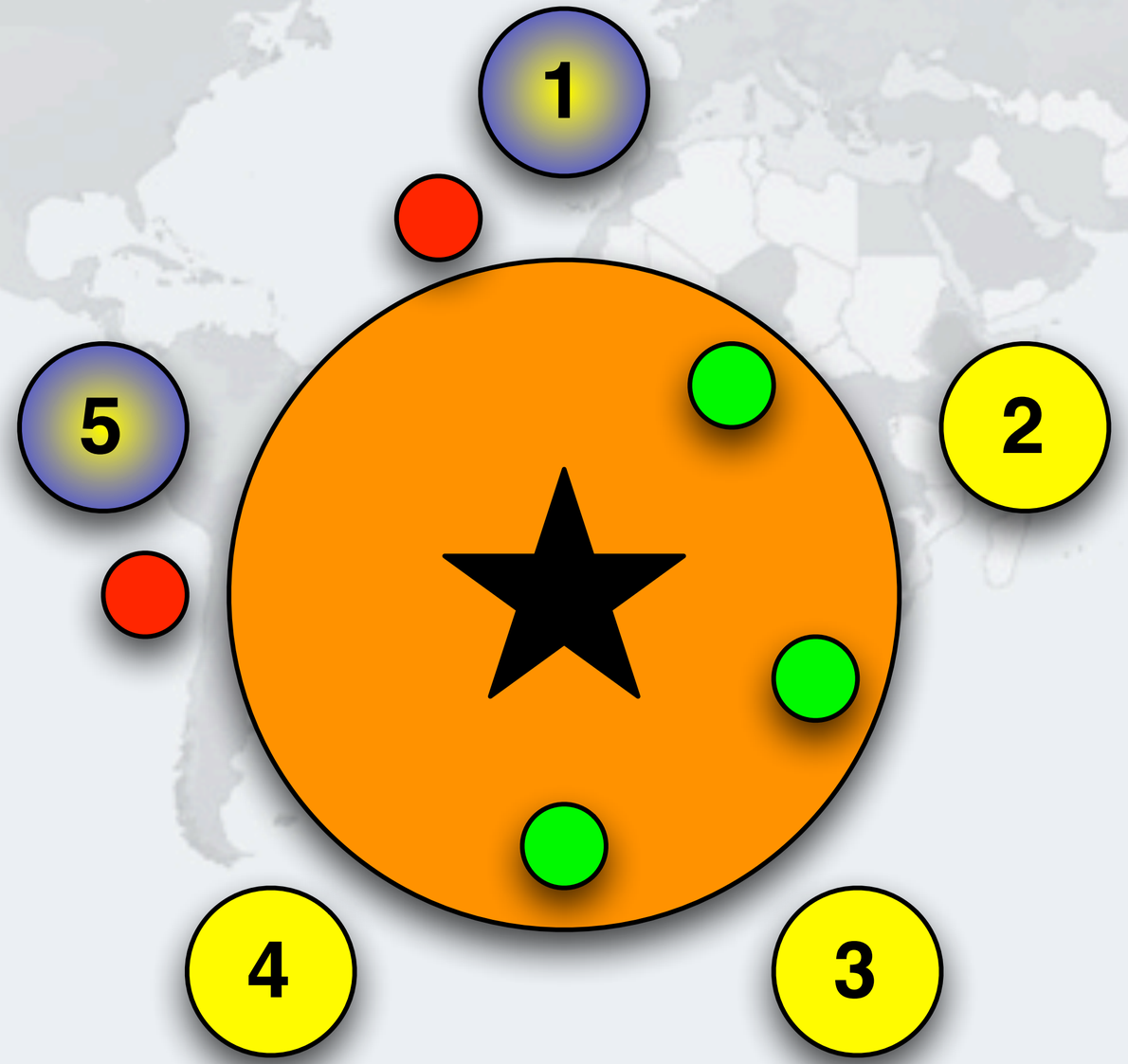
A Deadlock Can Easily Happen With This Design



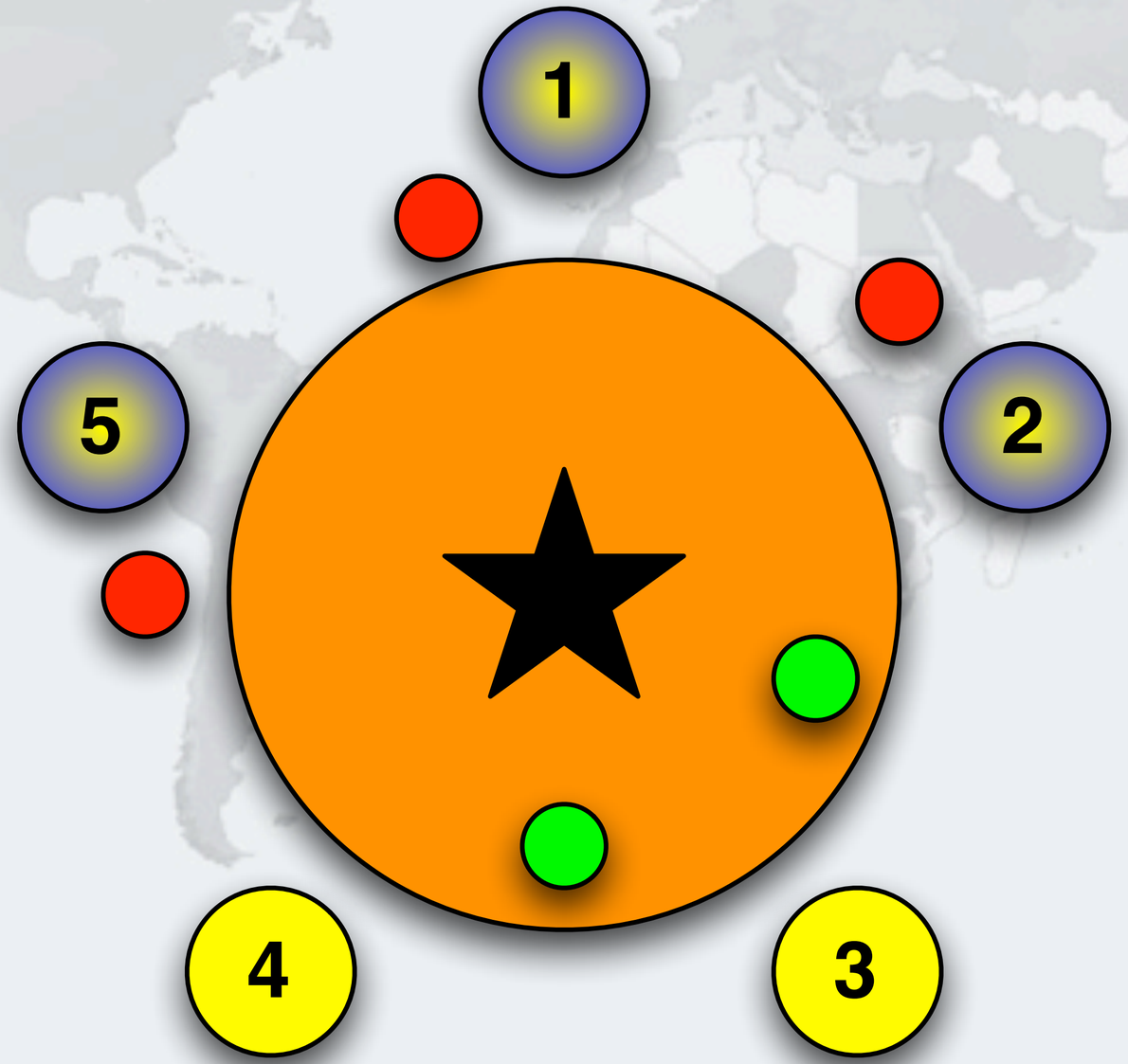
Philosopher 5 Wants To Drink, Takes Right Cup



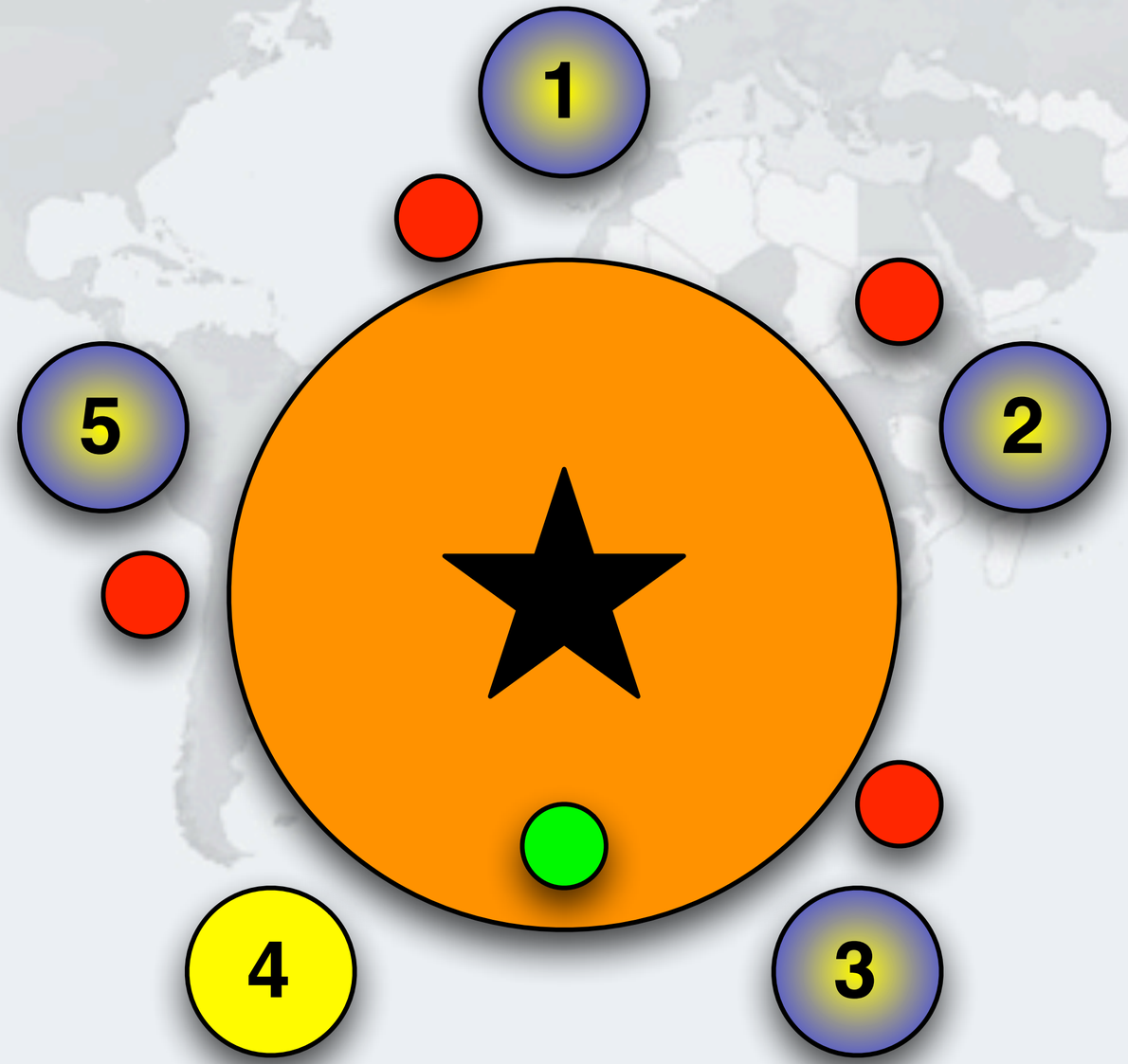
Philosopher 1 Wants To Drink, Takes Right Cup



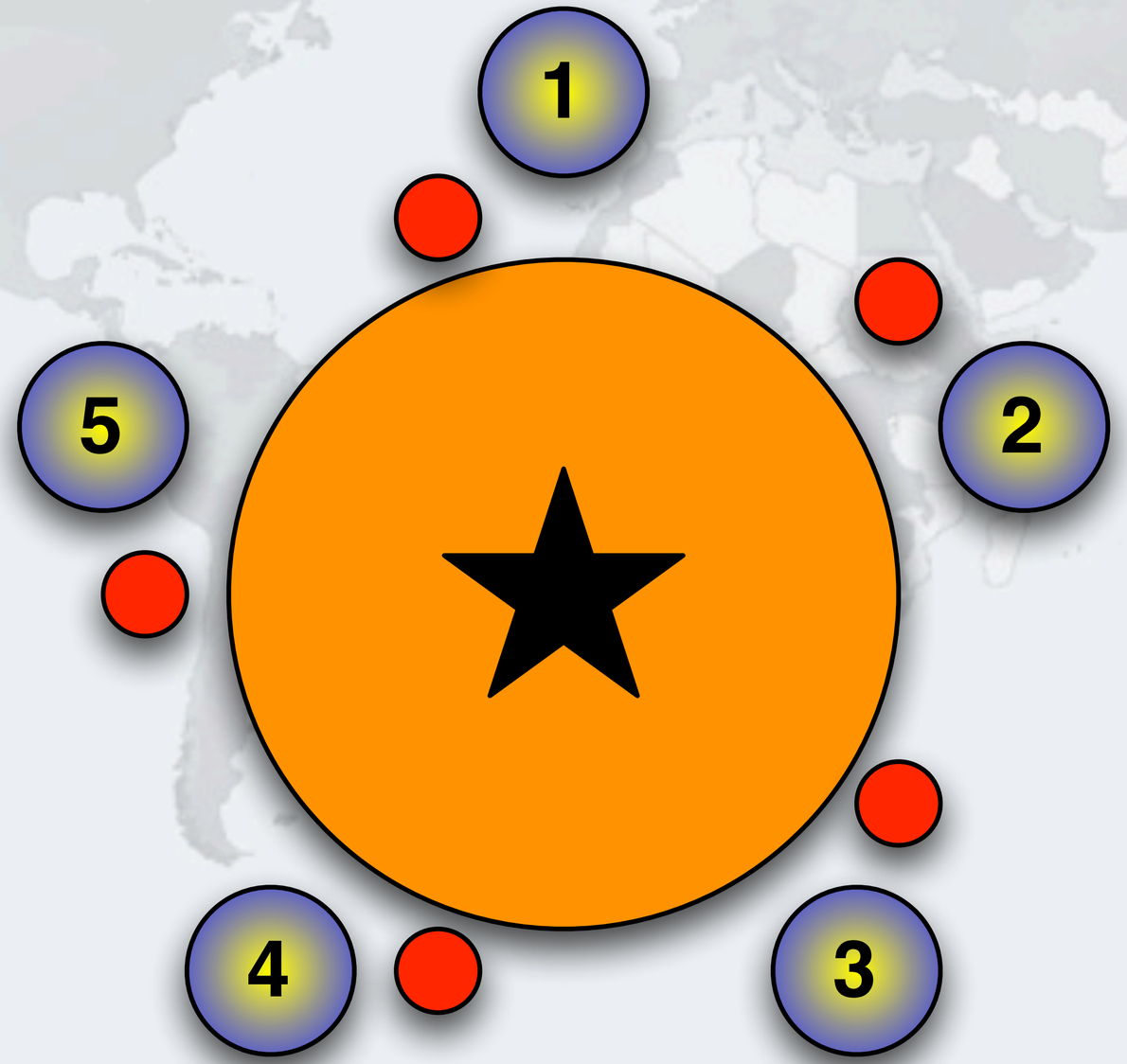
Philosopher 2 Wants To Drink, Takes Right Cup



Philosopher 3 Wants To Drink, Takes Right Cup

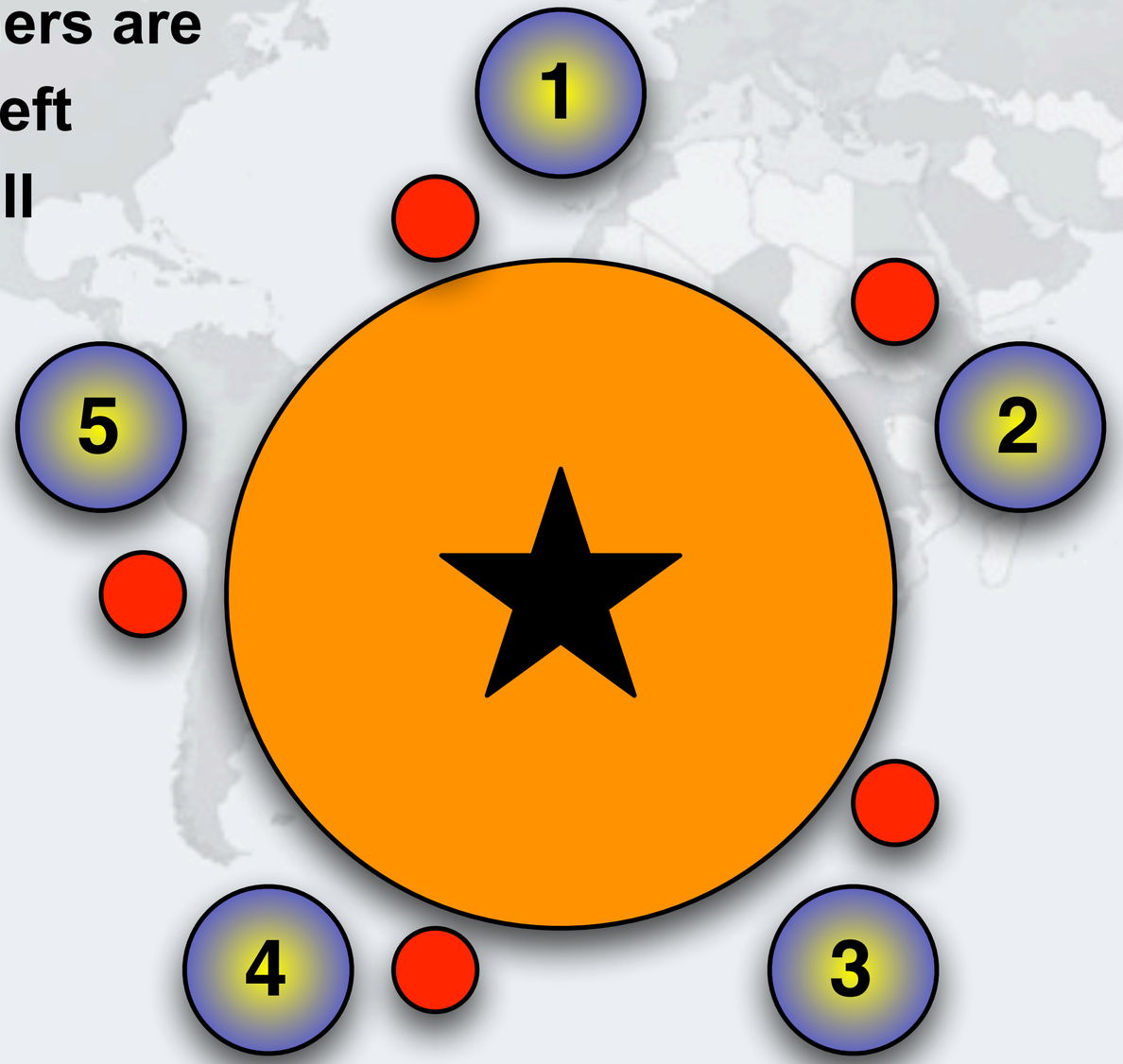


Philosopher 4 Wants To Drink, Takes Right Cup



Deadlock!

- All the philosophers are waiting for their left cups, but they will never become available

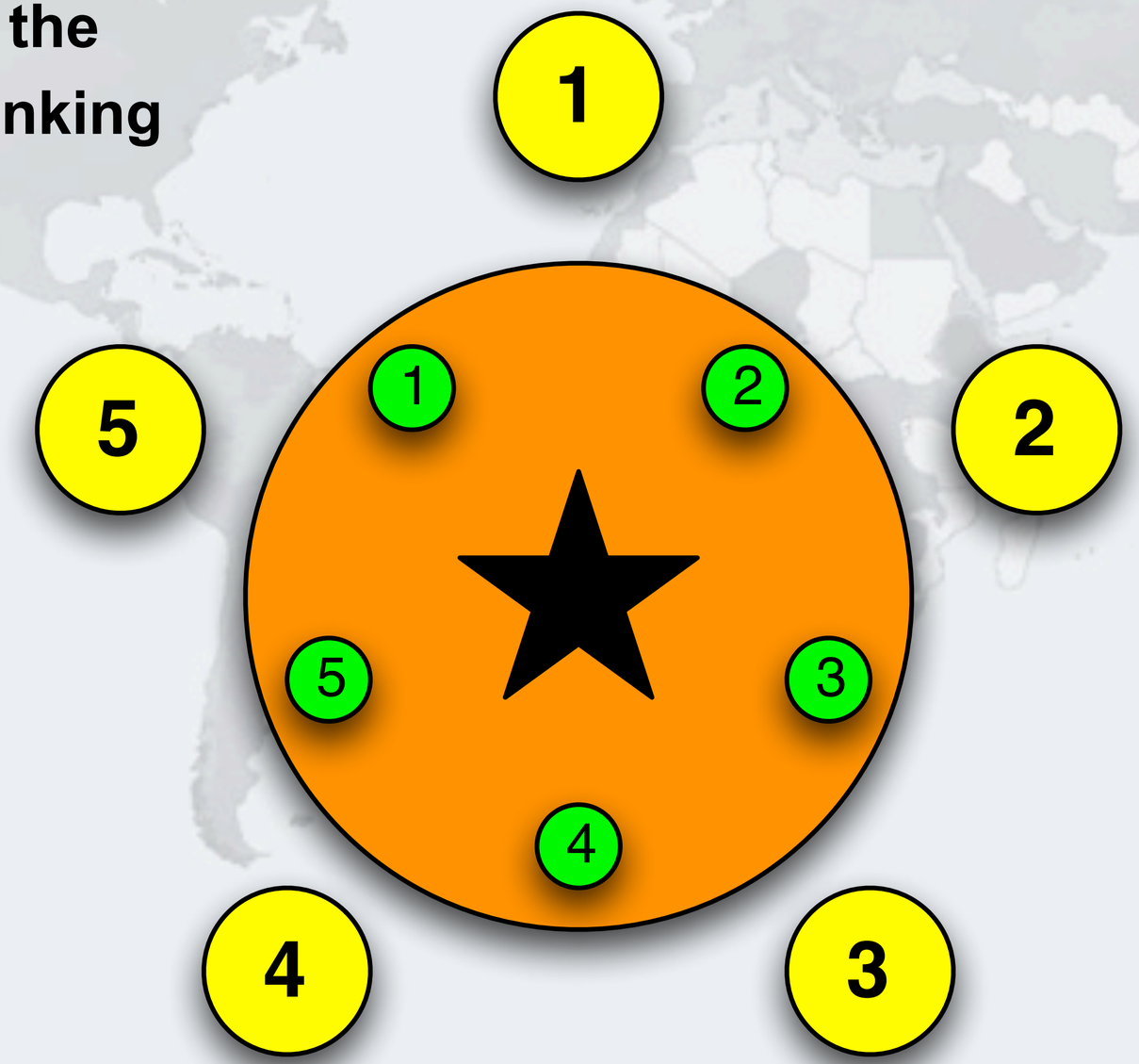


Global Order With Boozing Philosophers

- **If all philosophers hold one cup, we deadlock**
  - **Our solution must prevent all philosophers from holding one cup**
- **We can solve the deadlock with the "dining philosophers" by requiring that locks are always acquired in a set order**
  - **For example, we can make a rule that philosophers always first take the cup with the largest number**
    - **If it is not available, we block until it becomes available**
  - **And return the cup with the lowest number first**

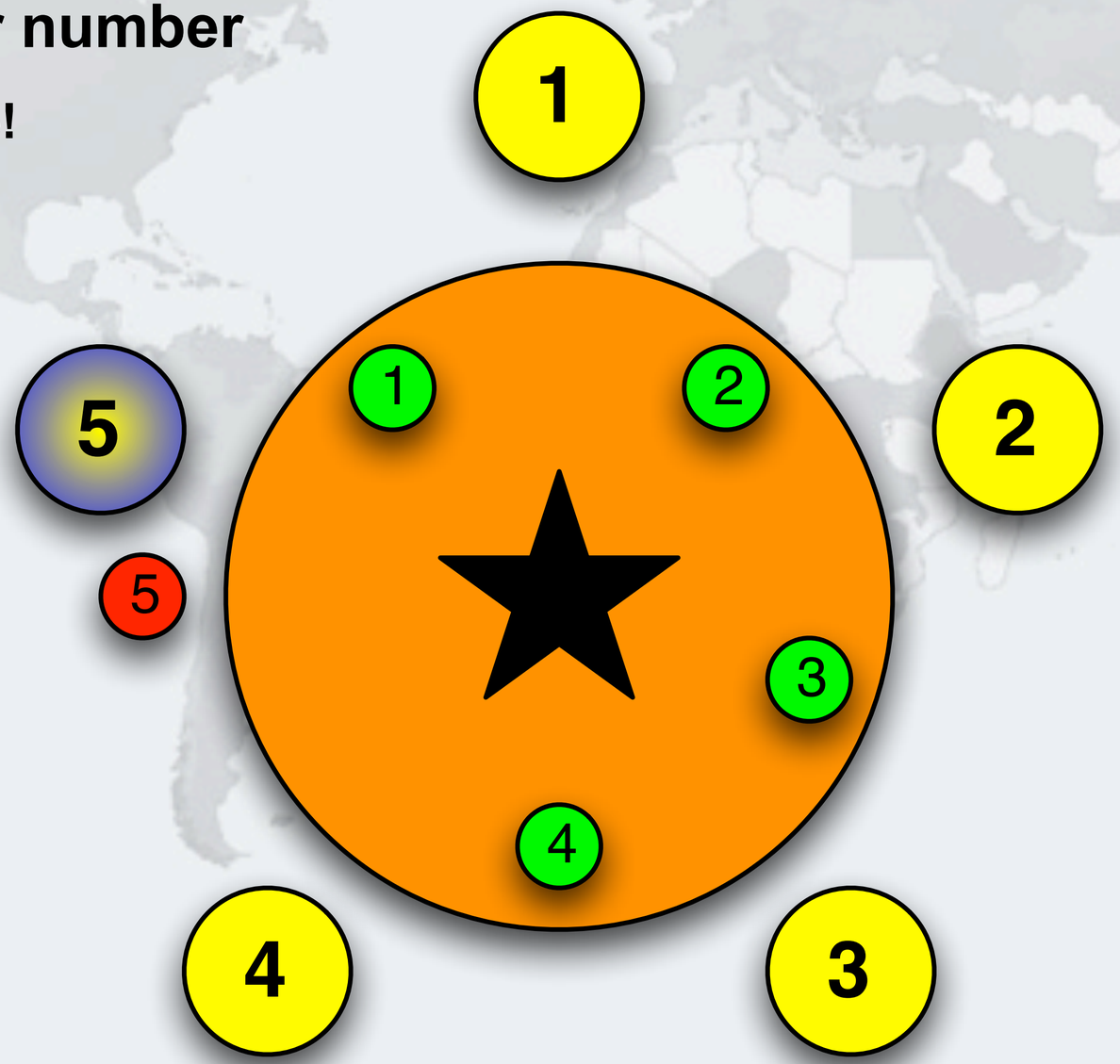
Global Lock Ordering

- **We start with all the philosophers thinking**



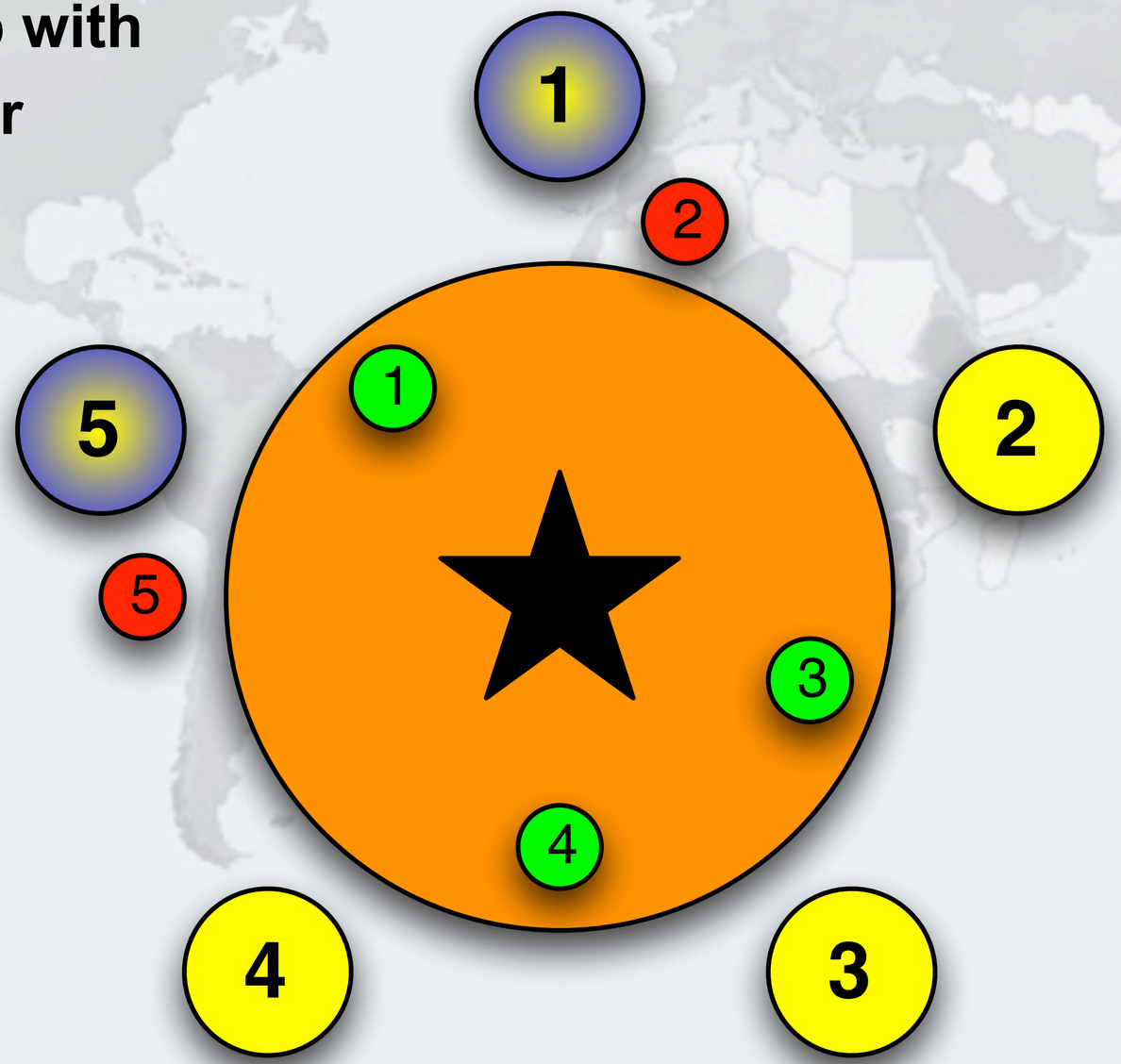
Philosopher 5 Takes Cup 5

- **Cup 5 has higher number**
  - **Remember our rule!**

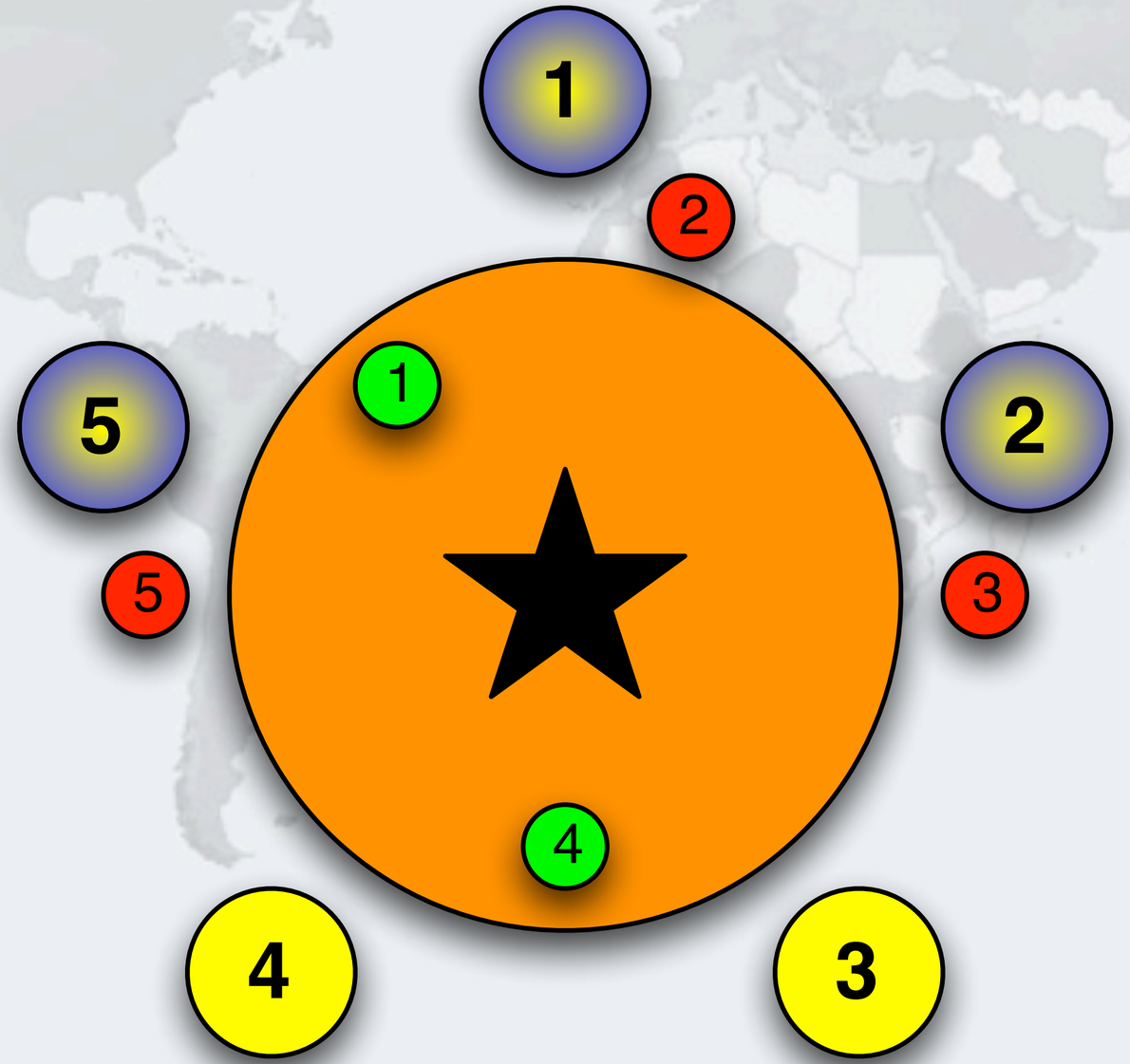


Philosopher 1 Takes Cup 2

- **Must take the cup with the higher number first**
  - **In this case cup 2**

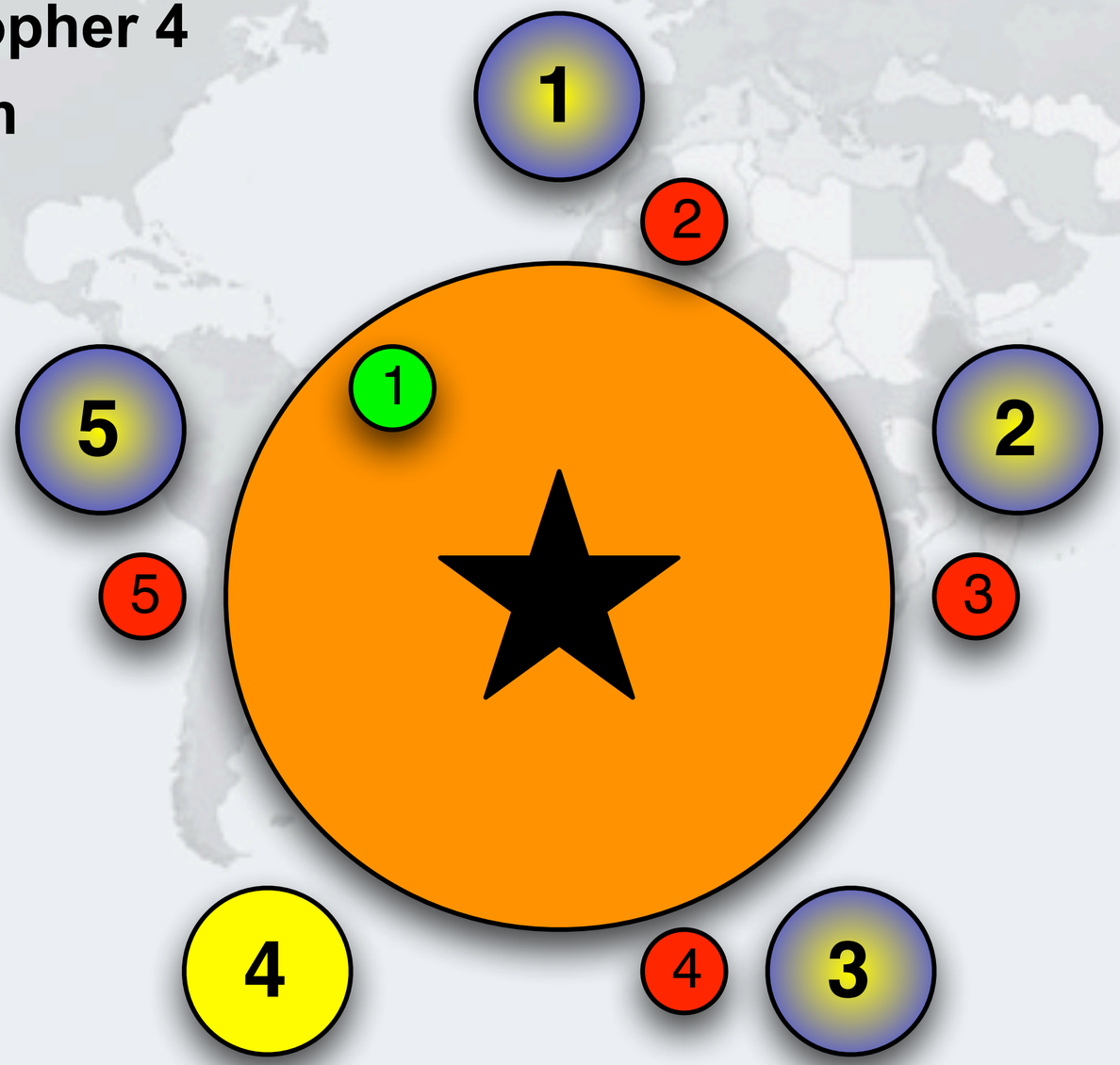


Philosopher 2 Takes Cup 3

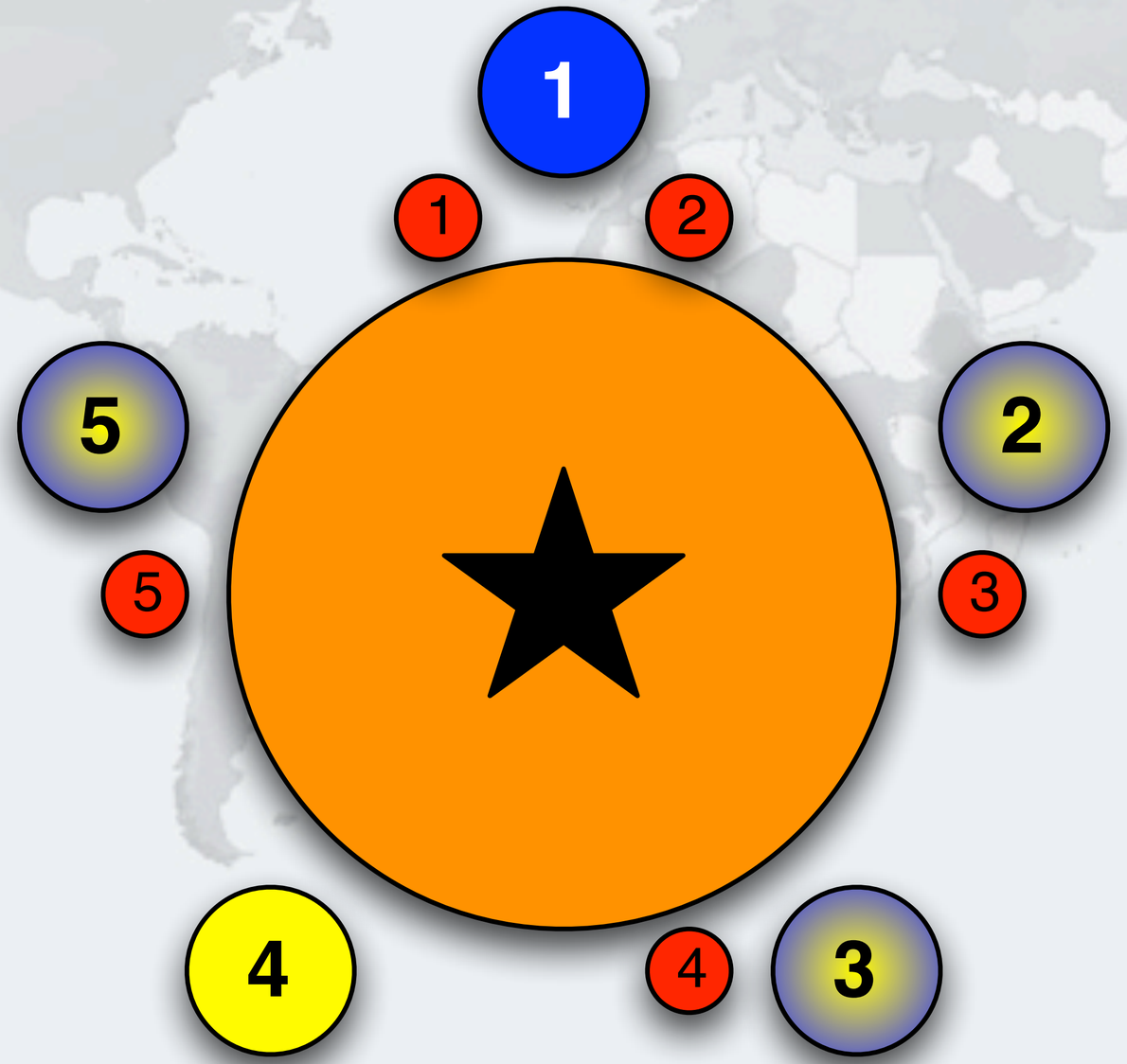


Philosopher 3 Takes Cup 4

- **Note that philosopher 4 is prevented from holding one cup**

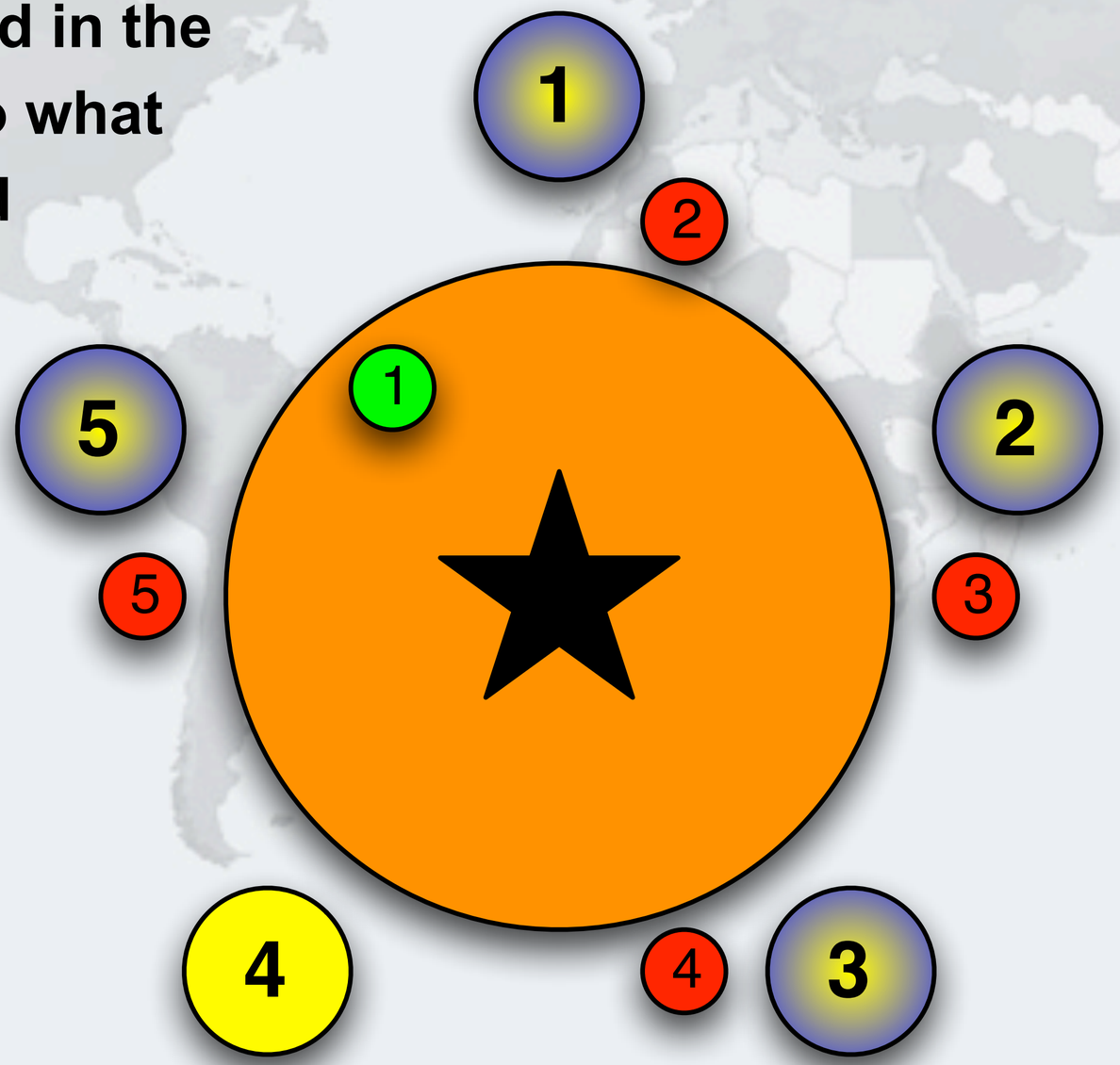


Philosopher 1 Takes Cup 1 - Drinking

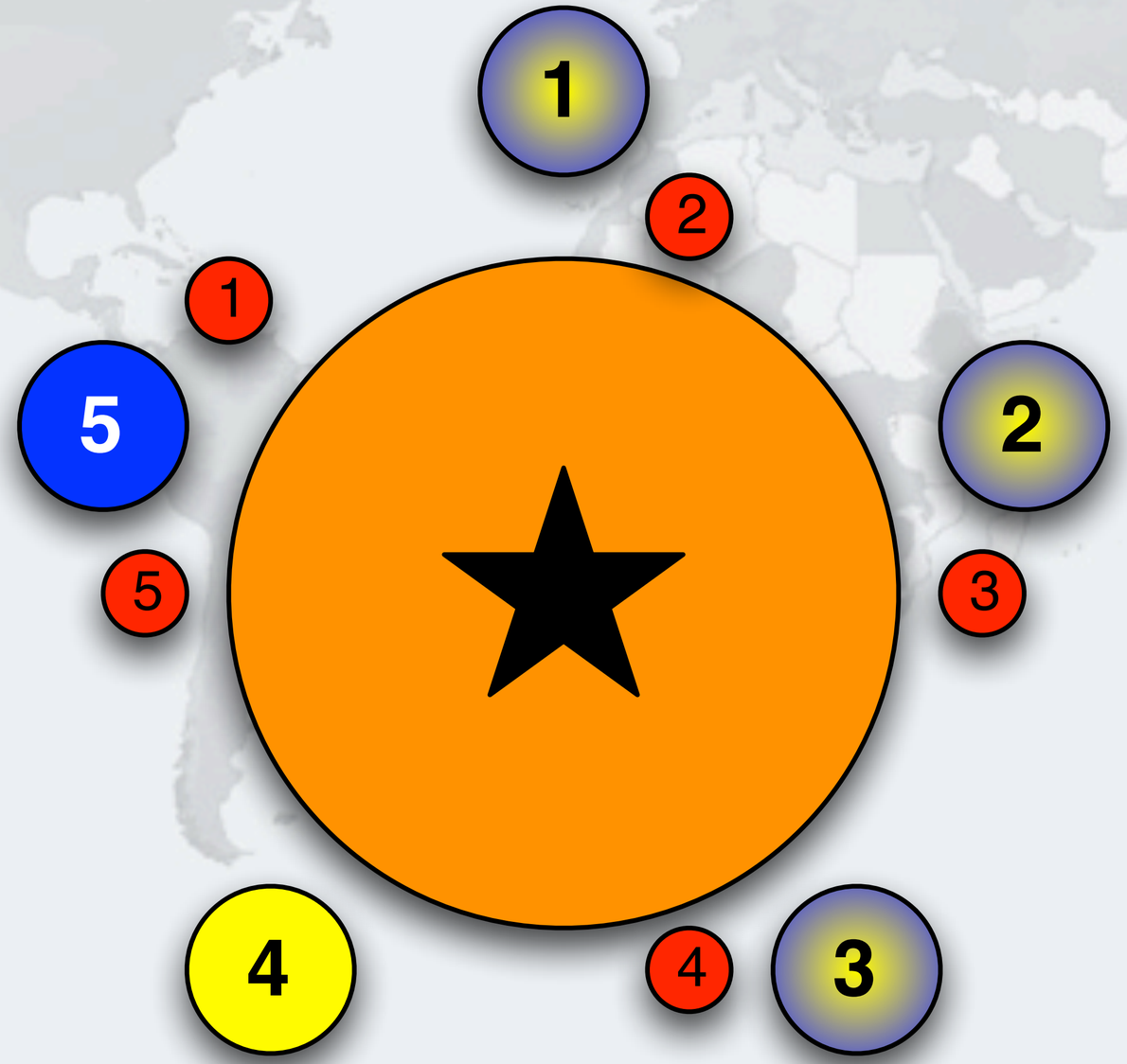


Philosopher 1 Returns Cup 1

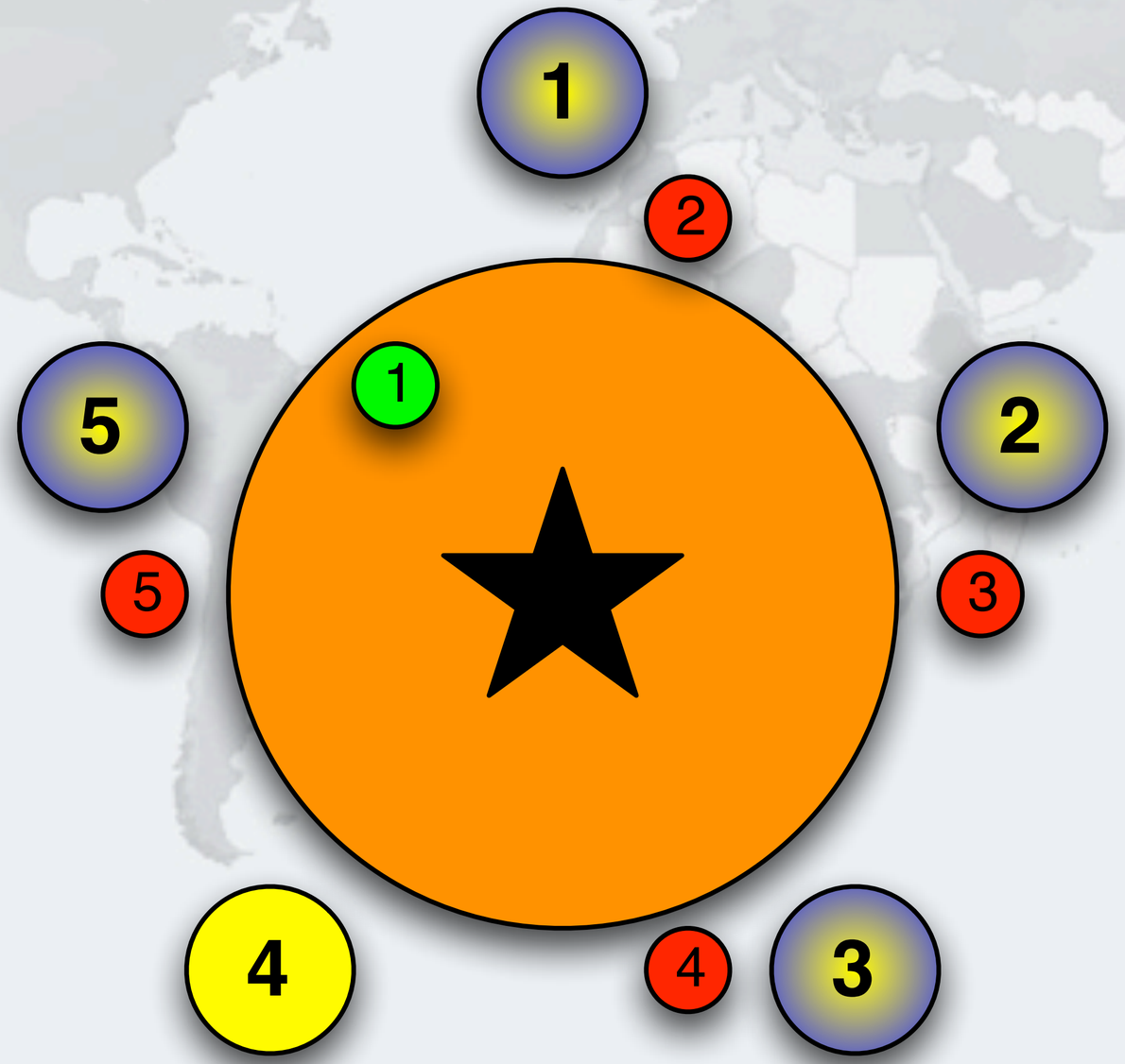
- **Cups are returned in the opposite order to what they are acquired**



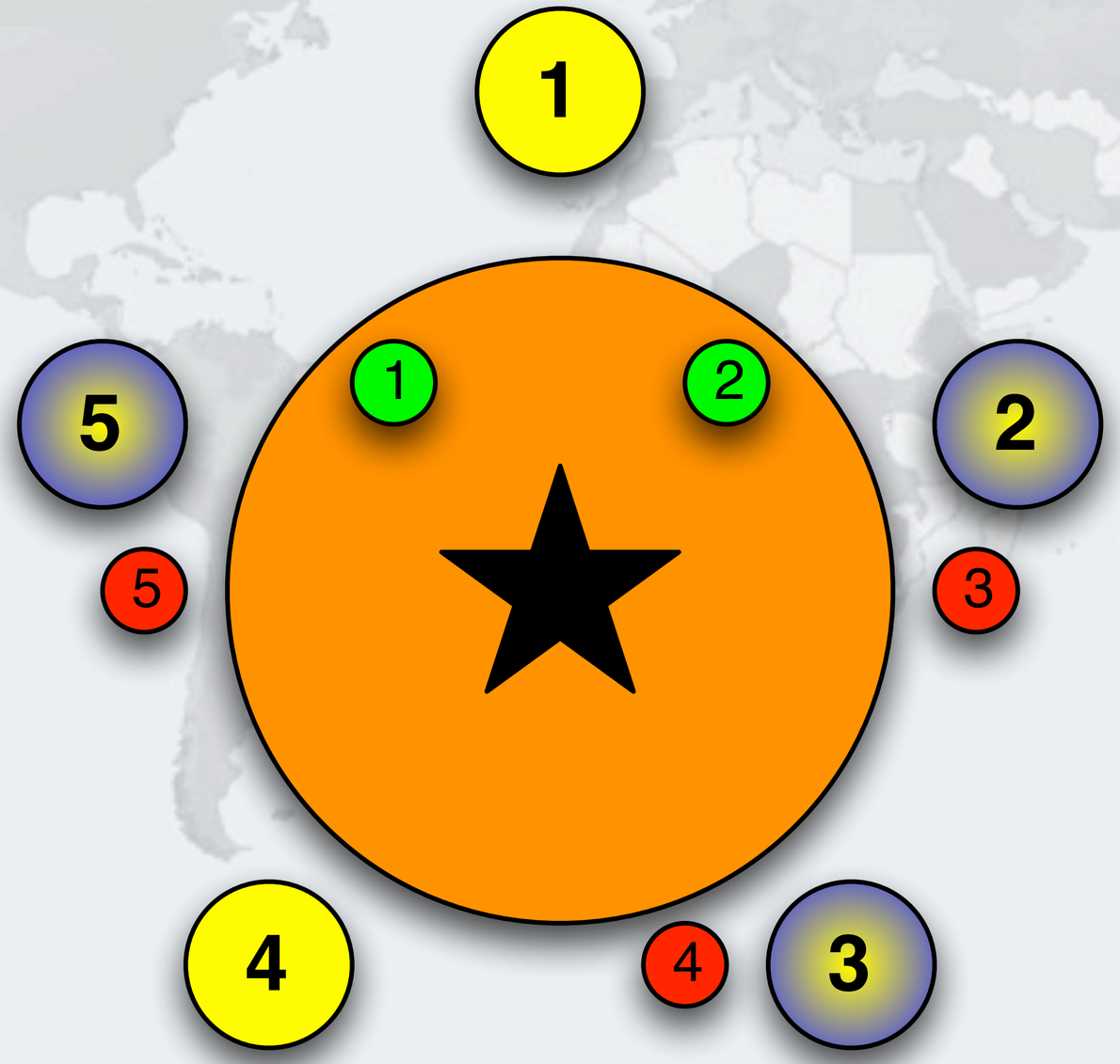
Philosopher 5 Takes Cup 1 - Drinking



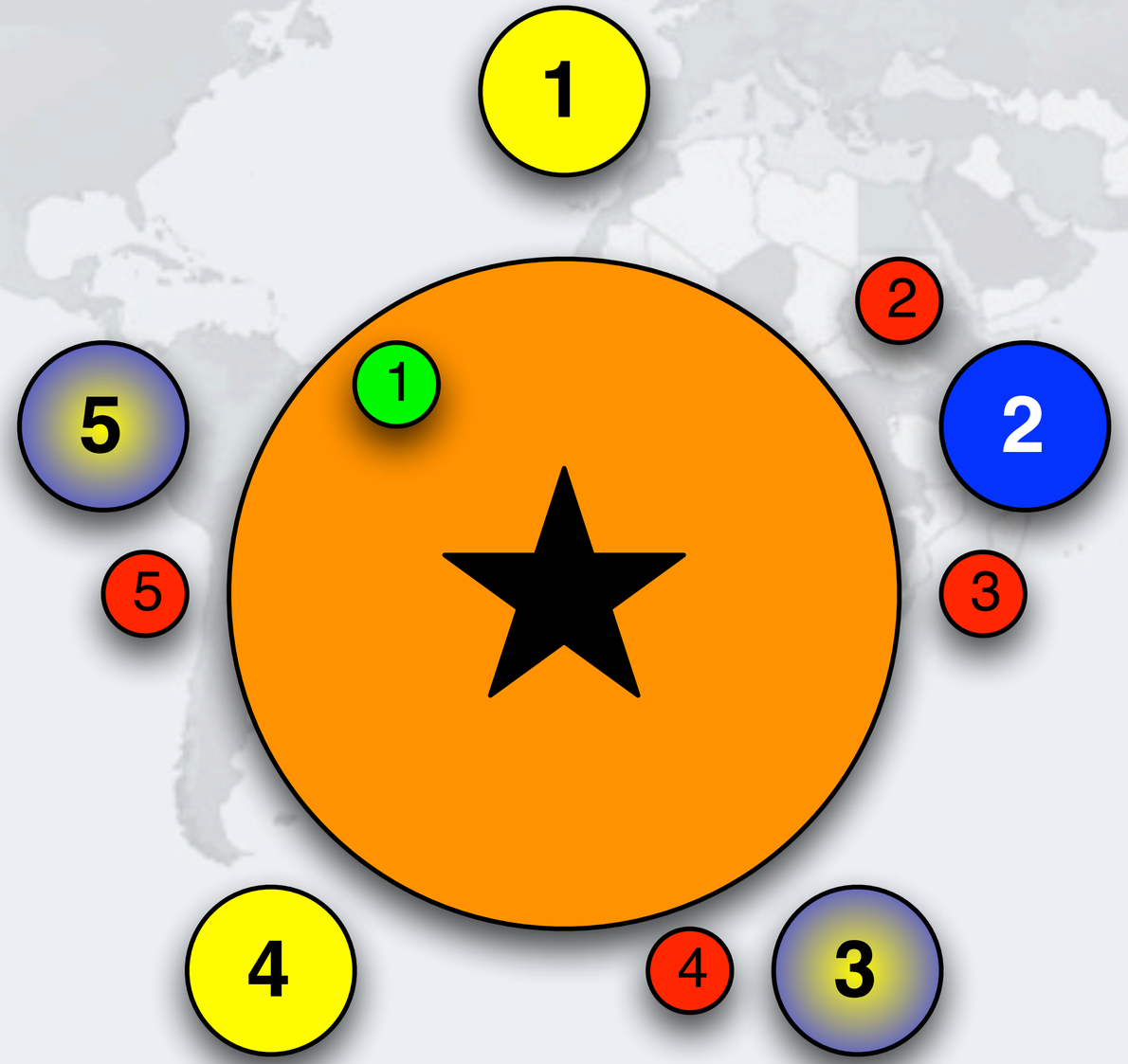
Philosopher 5 Returns Cup 1



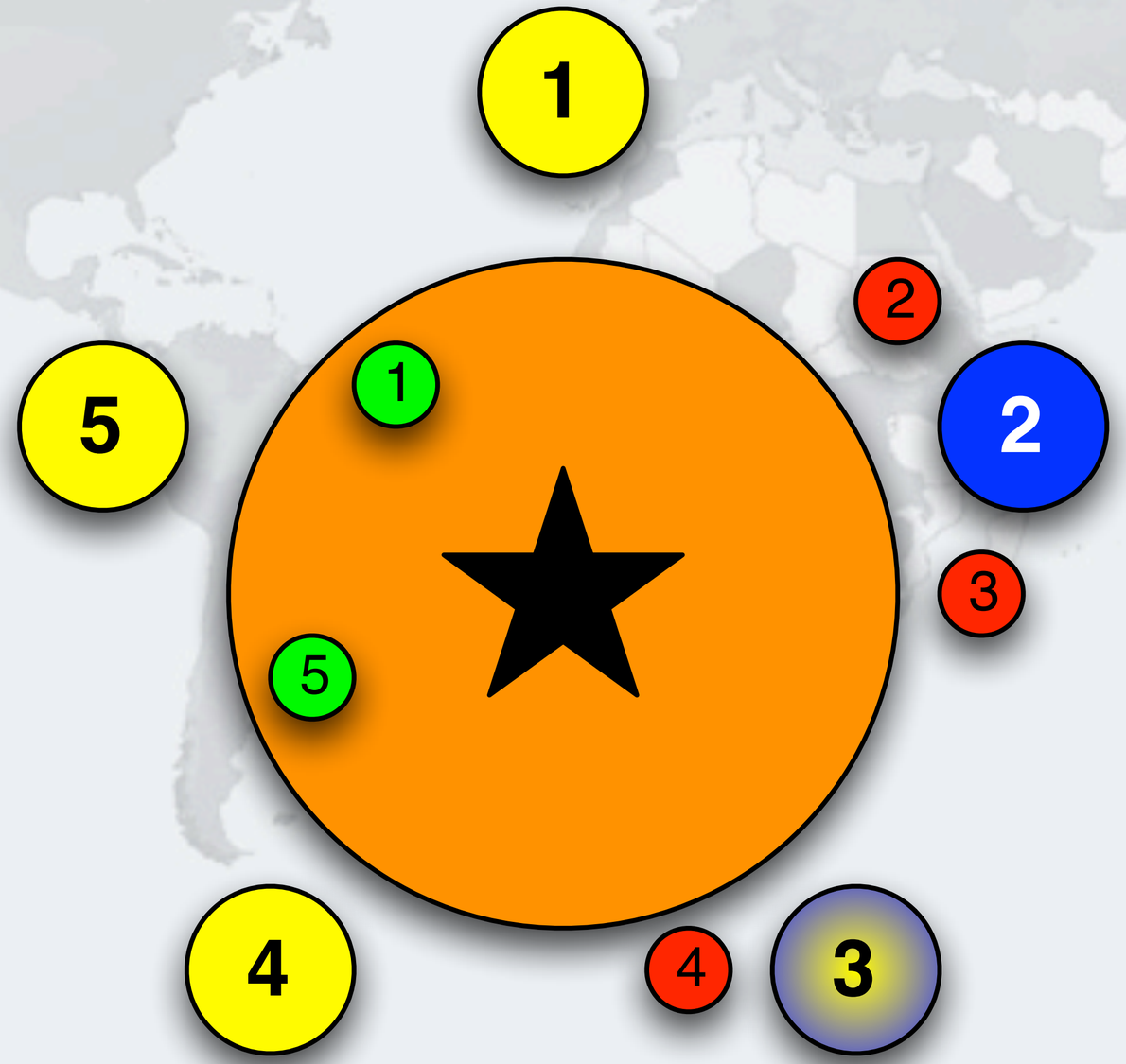
Philosopher 1 Returns Cup 2



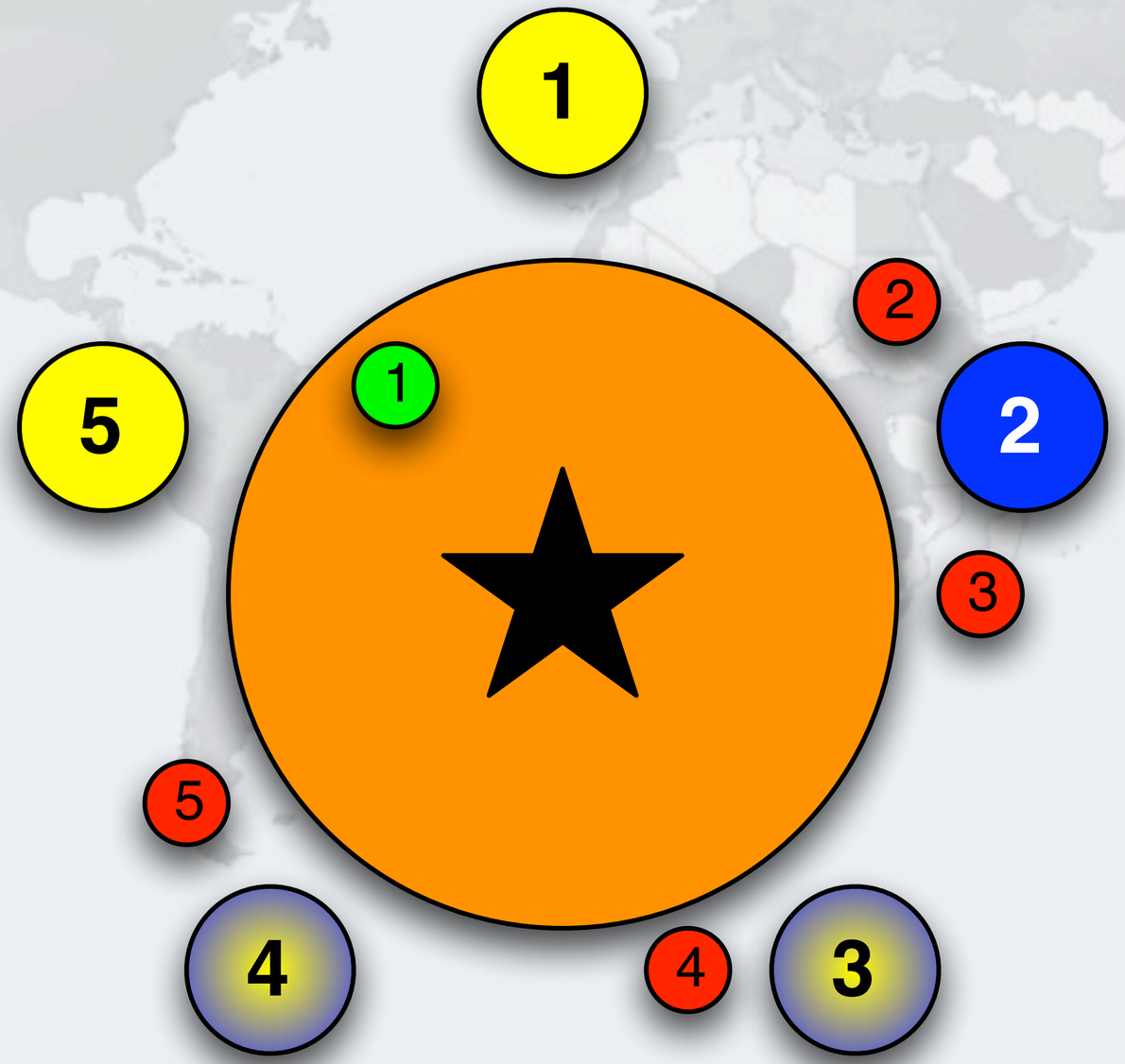
Philosopher 2 Takes Cup 2 - Drinking



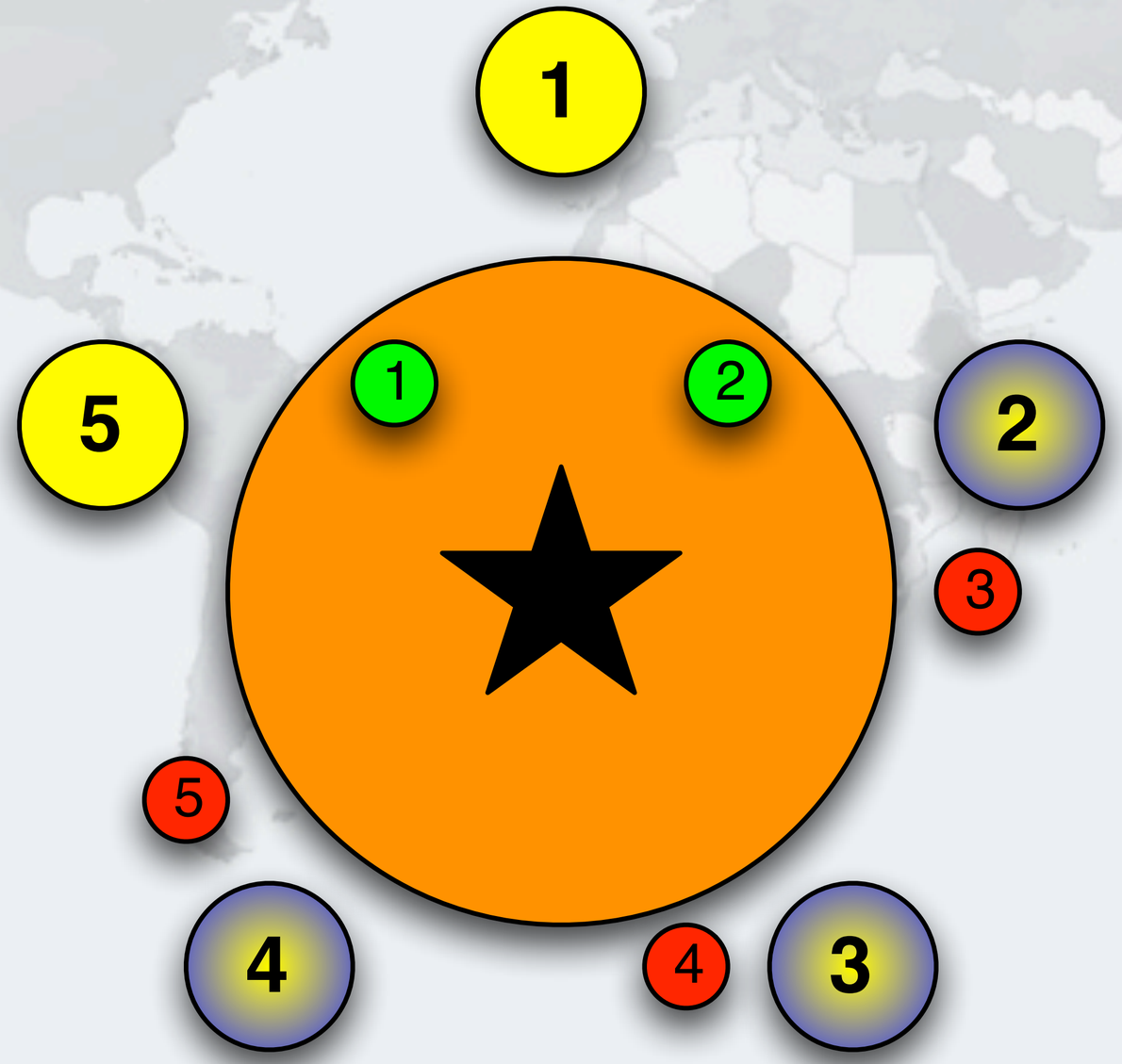
Philosopher 5 Returns Cup 5



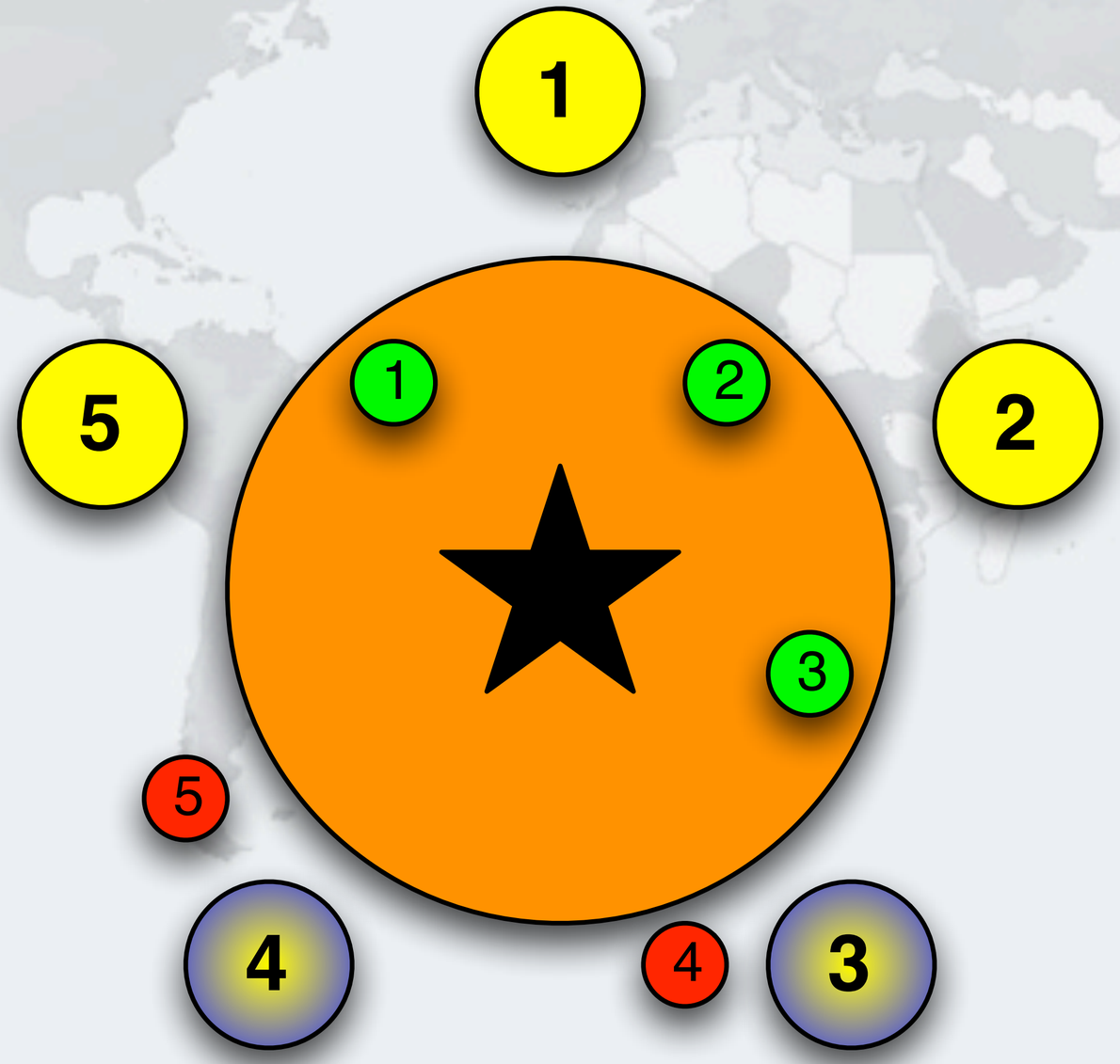
Philosopher 4 Takes Cup 5



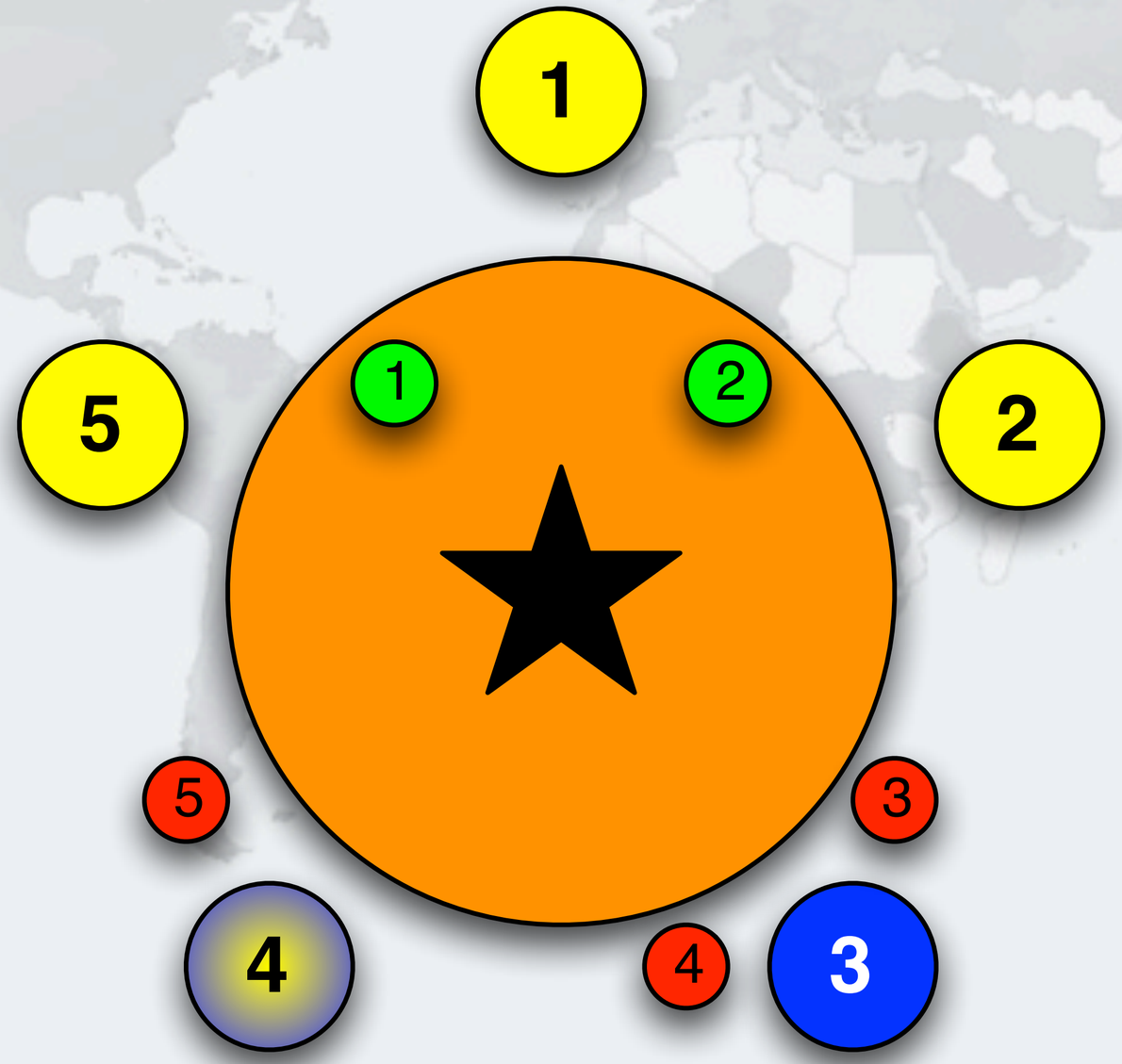
Philosopher 2 Returns Cup 2



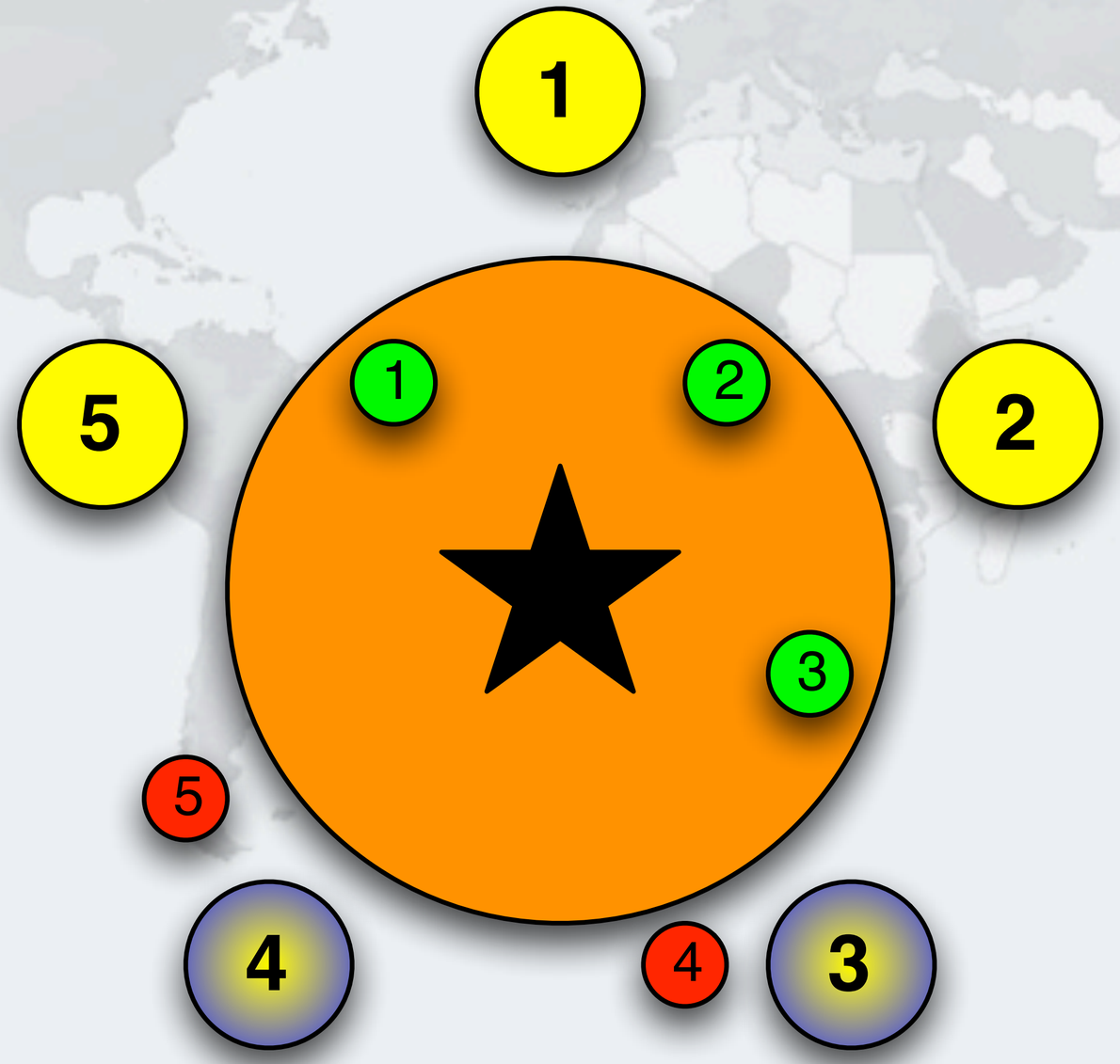
Philosopher 2 Returns Cup 3



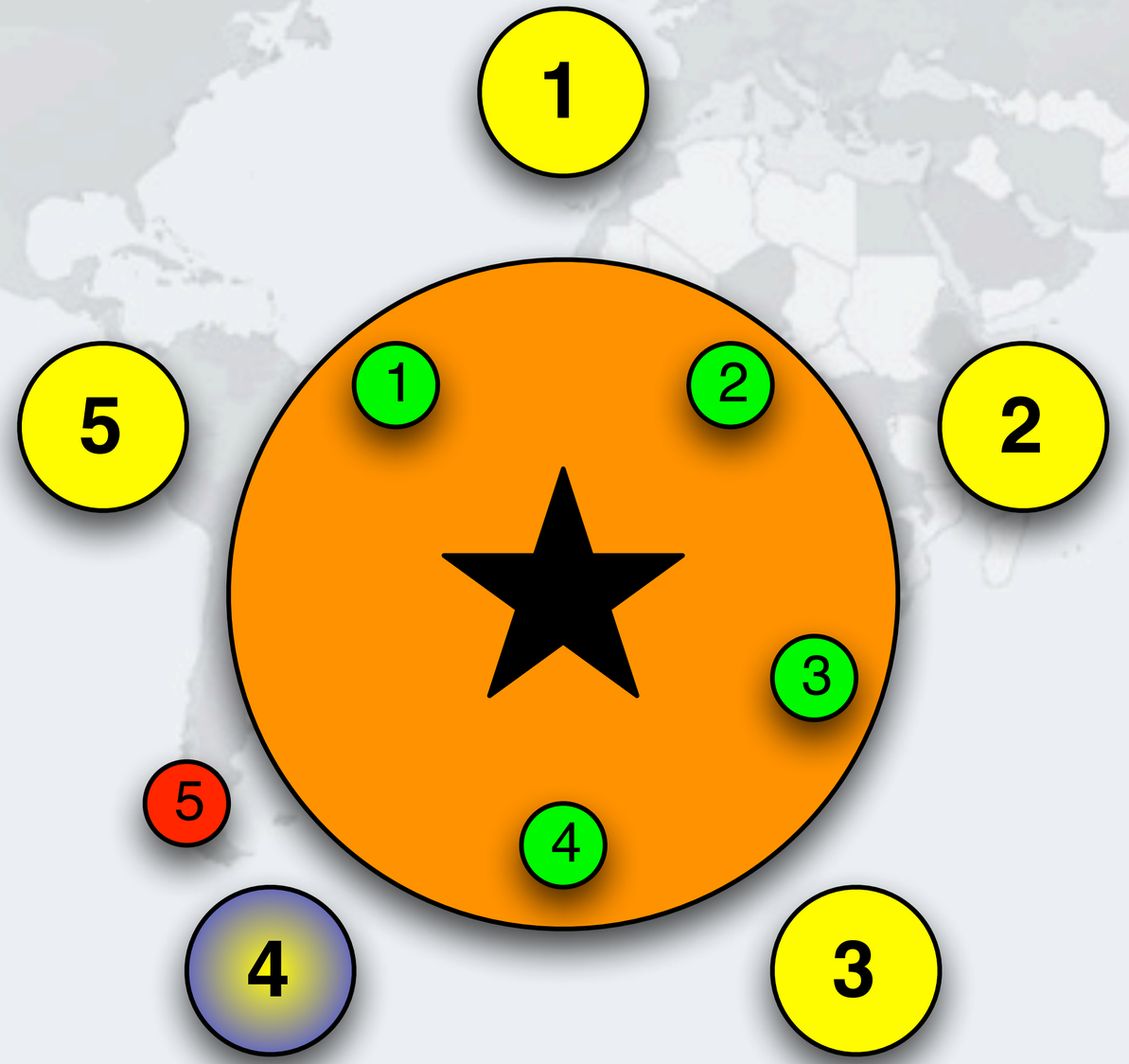
Philosopher 3 Takes Cup 3 - Drinking



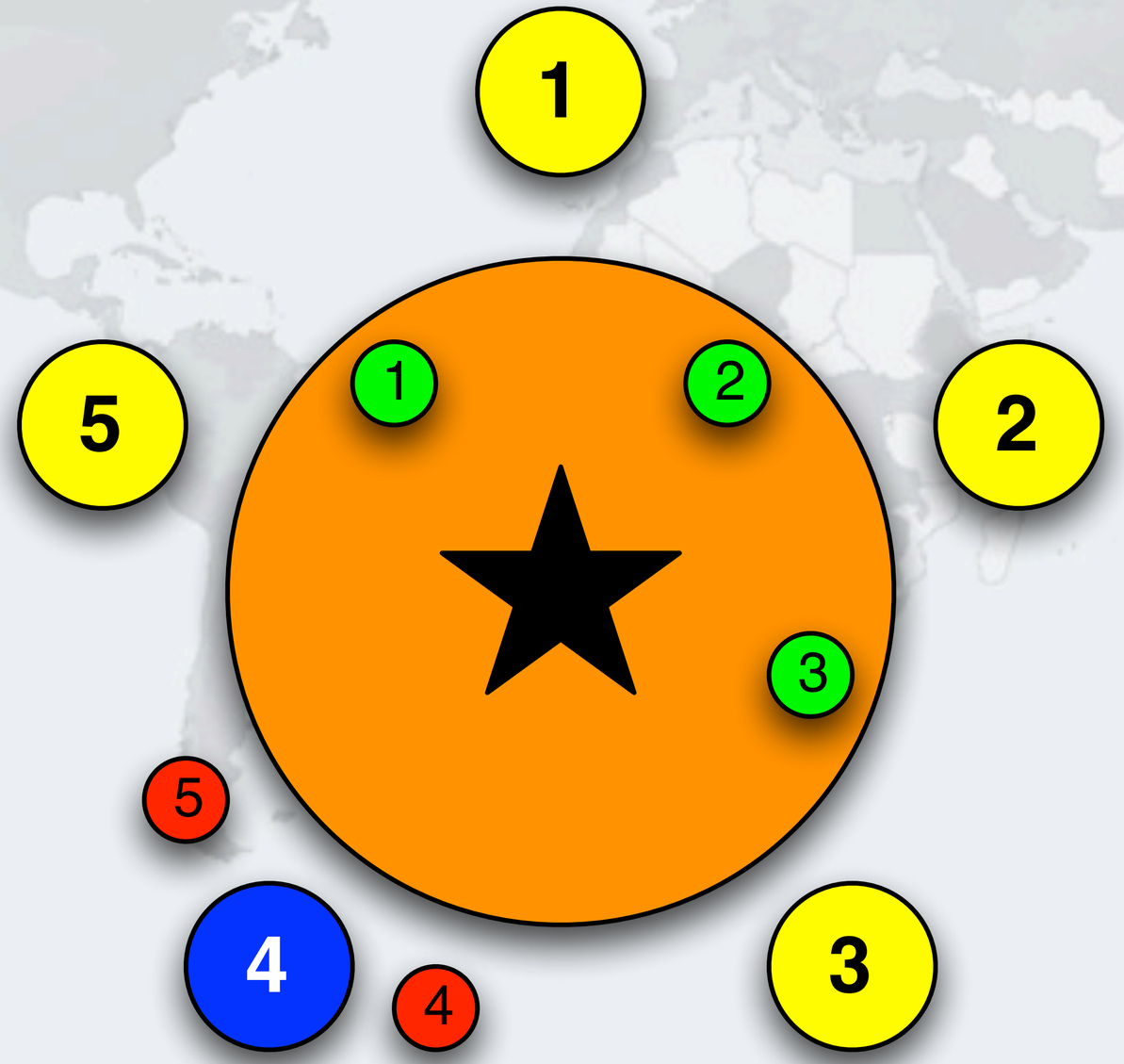
Philosopher 3 Returns Cup 3



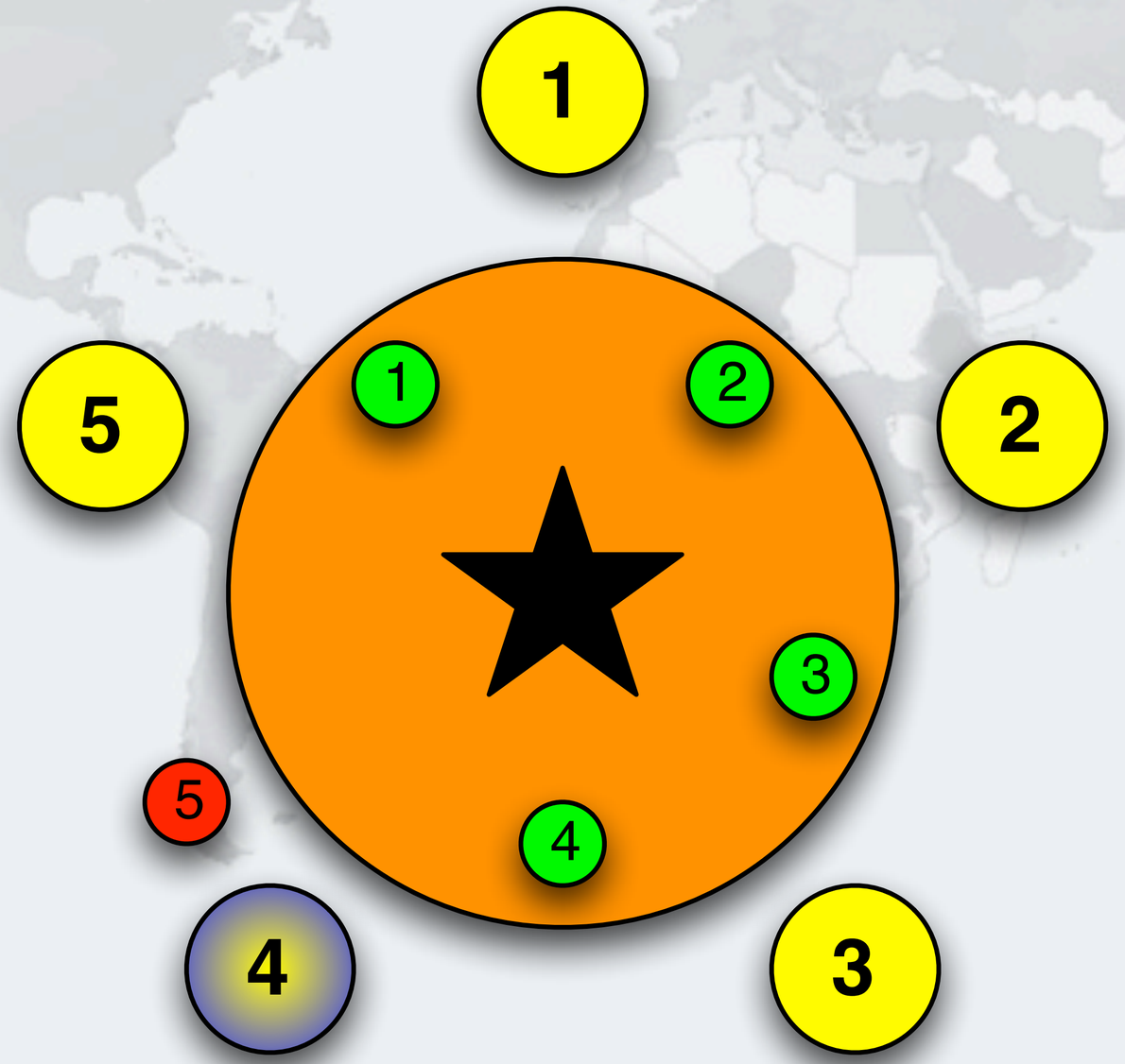
Philosopher 3 Returns Cup 4



Philosopher 4 Takes Cup 4 - Drinking

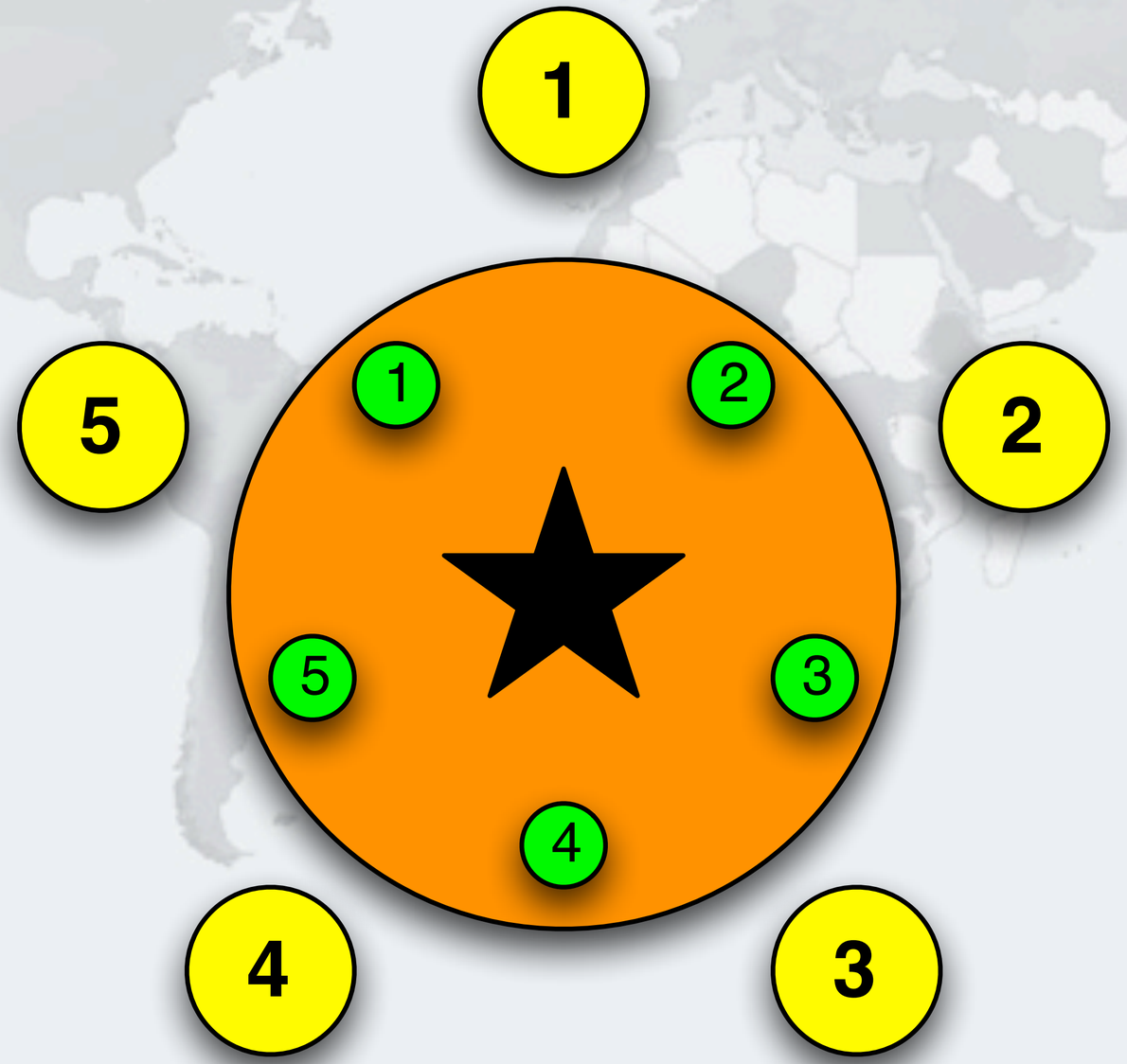


Philosopher 4 Returns Cup 4



Philosopher 4 Returns Cup 5

- **Deadlock free!**

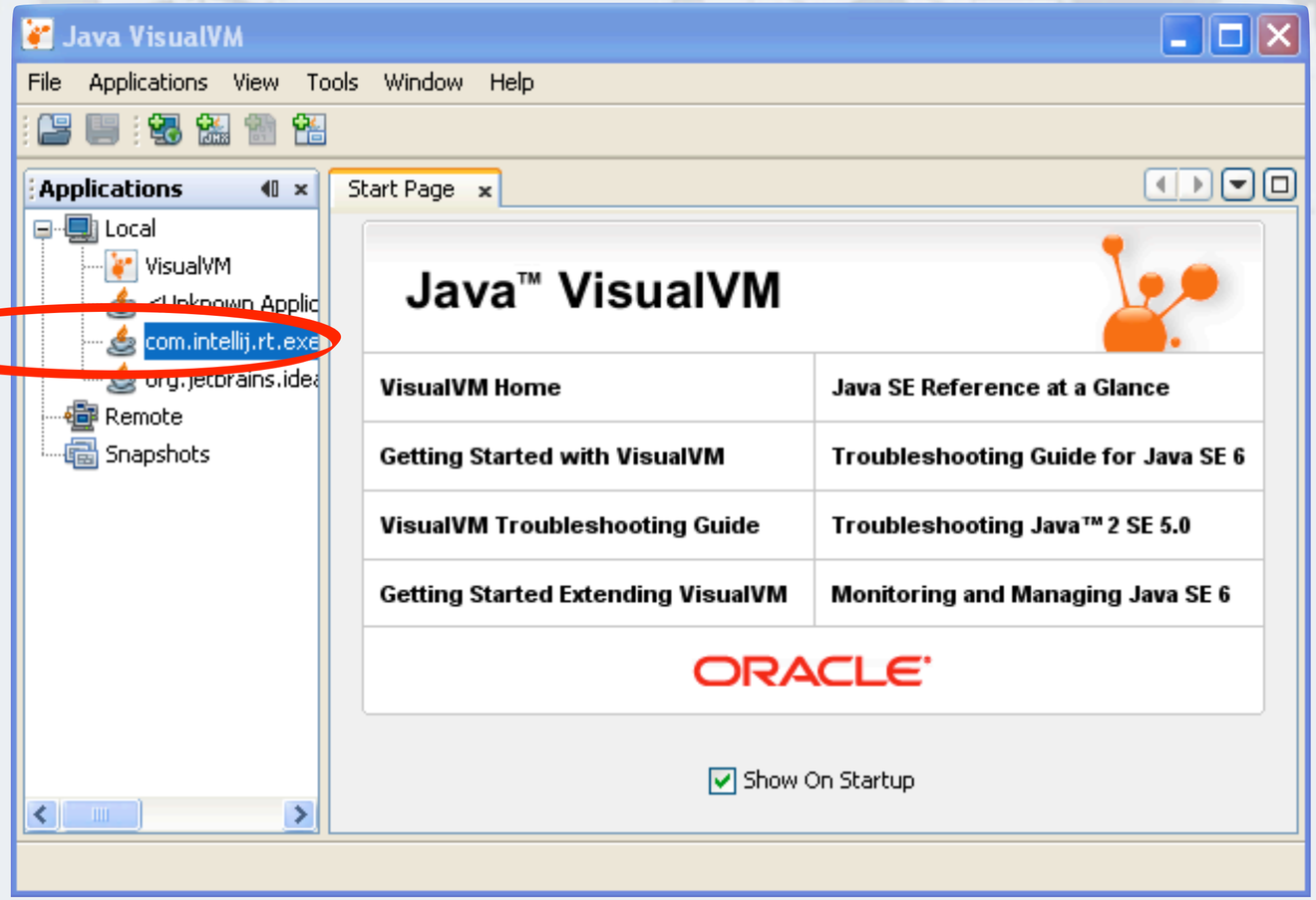


Deadlock Is Avoided

- **Impossible for all philosophers to hold one cup**

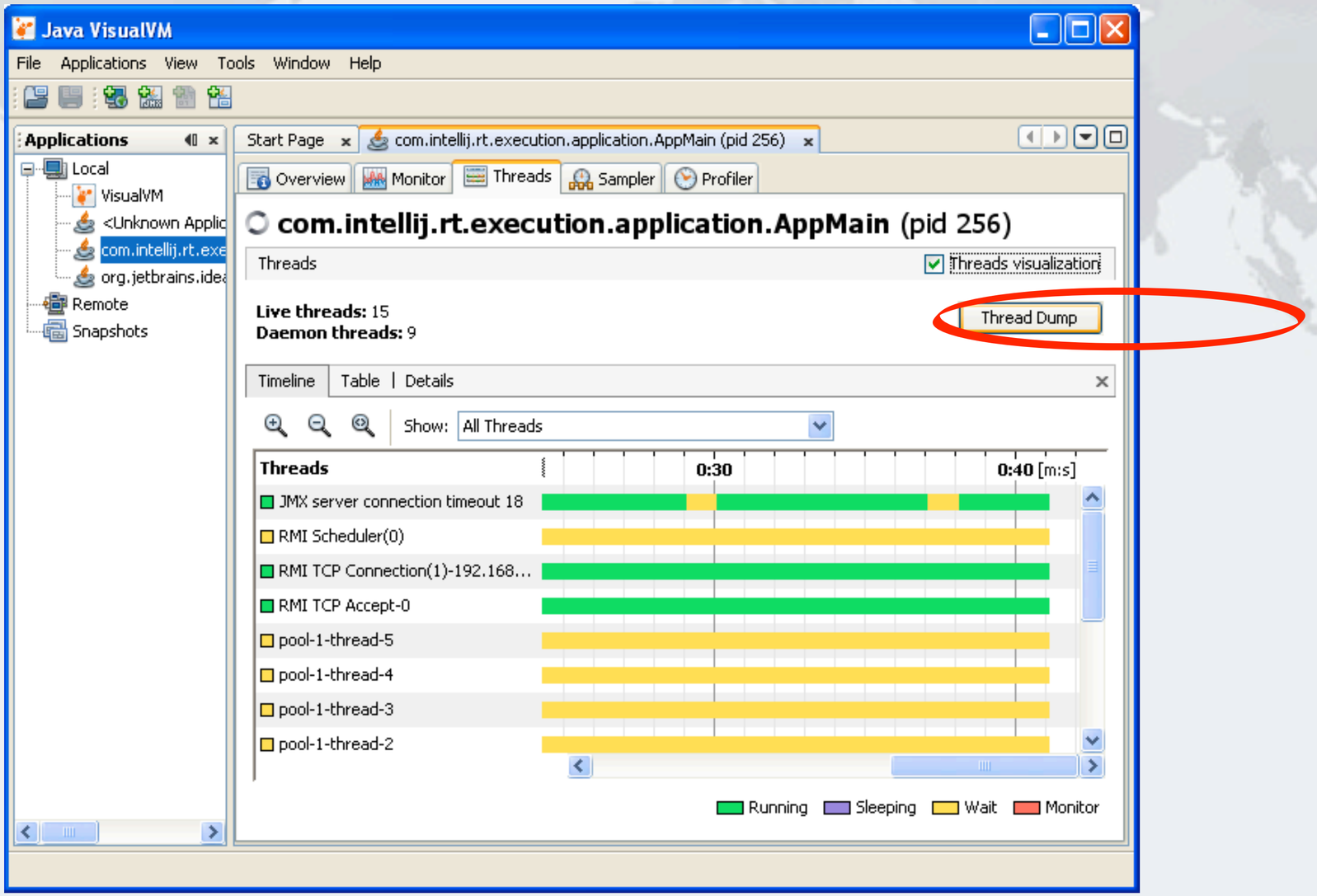
Capturing A Stack Trace

- **JVisualVM is a tool for monitoring what the JVM is doing**
  - **Found in the JDK/bin directory**
  - **Double-click on application**

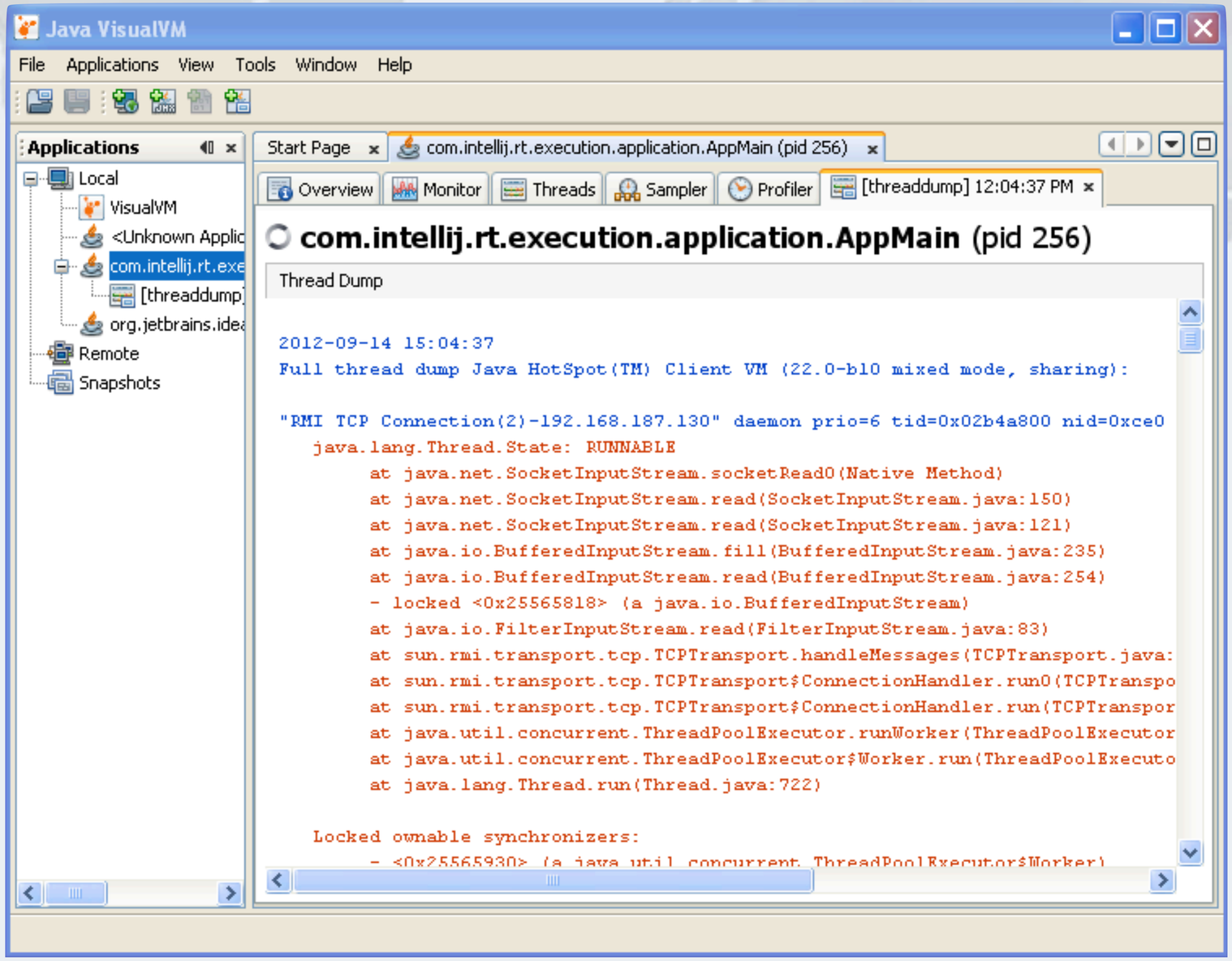


Click On "Threads" Tab

- **Click on "Thread Dump" button**



Stack Trace Shows What Threads Are Doing



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com.intellij.rt.execution.application.AppMain (pid 256)

Overview | Monitor | Threads | Sampler | Profiler | [threaddump] 12:04:37 PM

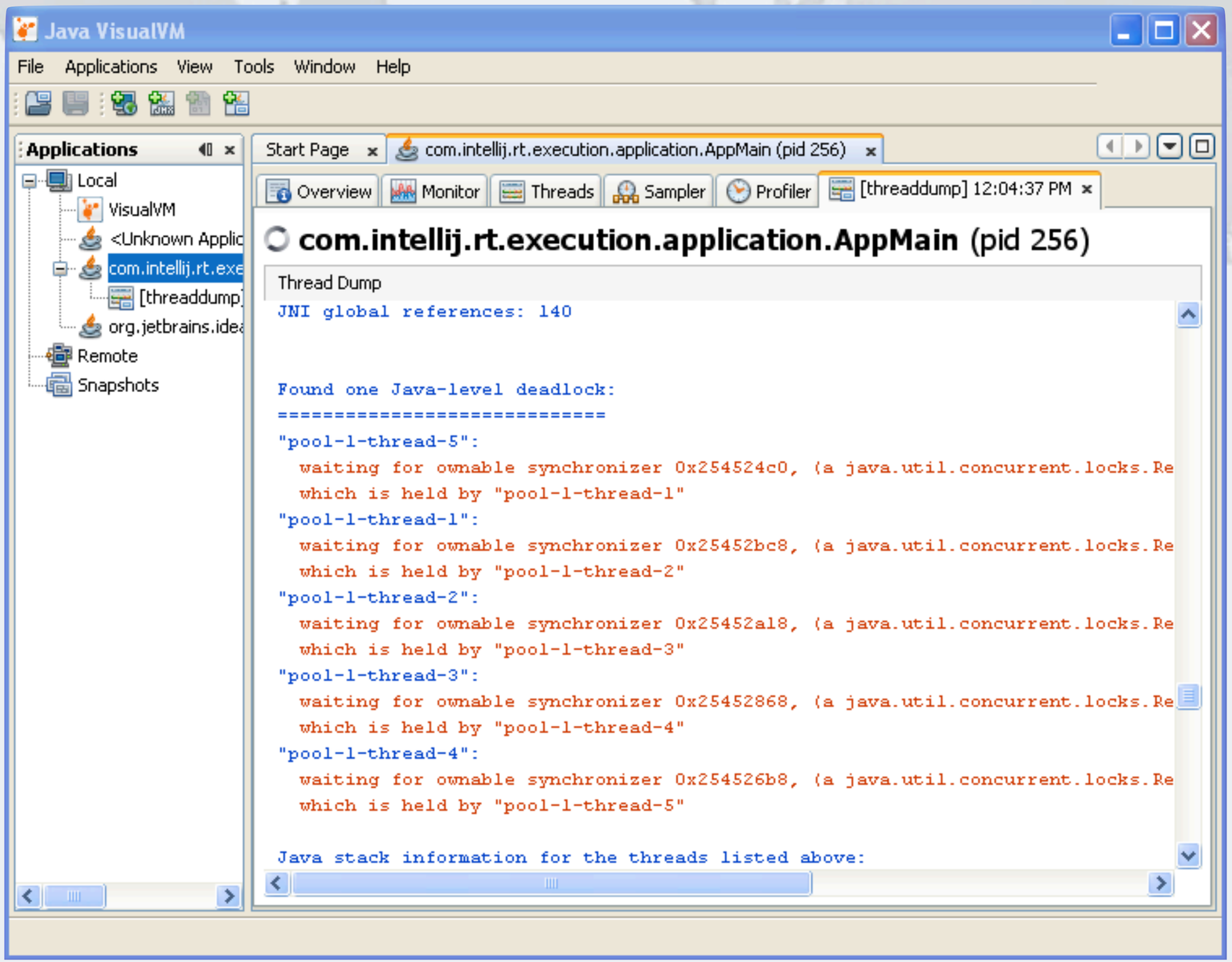
com.intellij.rt.execution.application.AppMain (pid 256)

Thread Dump

```
2012-09-14 15:04:37
Full thread dump Java HotSpot(TM) Client VM (22.0-b10 mixed mode, sharing):

"RMI TCP Connection(2)-192.168.187.130" daemon prio=6 tid=0x02b4a800 nid=0xc
   java.lang.Thread.State: RUNNABLE
        at java.net.SocketInputStream.socketRead0(Native Method)
        at java.net.SocketInputStream.read(SocketInputStream.java:150)
        at java.net.SocketInputStream.read(SocketInputStream.java:121)
        at java.io.BufferedInputStream.fill(BufferedInputStream.java:235)
        at java.io.BufferedInputStream.read(BufferedInputStream.java:254)
        - locked <0x25565818> (a java.io.BufferedInputStream)
        at java.io.FilterInputStream.read(FilterInputStream.java:83)
        at sun.rmi.transport.tcp.TCPTransport.handleMessages(TCPTransport.ja
        at sun.rmi.transport.tcp.TCPTransport$ConnectionHandler.run0(TCPTran
        at sun.rmi.transport.tcp.TCPTransport$ConnectionHandler.run(TCPTrans
```

It Can Even Detect A Java-level Deadlock



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com.intellij.rt.execution.application.AppMain (pid 256)

Overview | Monitor | Threads | Sampler | Profiler | [threaddump] 12:04:37 PM

com.intellij.rt.execution.application.AppMain (pid 256)

Thread Dump

```
JNI global references: 140


Found one Java-level deadlock:
=============================
"pool-1-thread-5":
  waiting for ownable synchronizer 0x254524c0, (a java.util.concurrent.locl
  which is held by "pool-1-thread-1"
"pool-1-thread-1":
  waiting for ownable synchronizer 0x25452bc8, (a java.util.concurrent.locl
  which is held by "pool-1-thread-2"
"pool-1-thread-2":
  waiting for ownable synchronizer 0x25452a18, (a java.util.concurrent.locl
  which is held by "pool-1-thread-3"
"pool-1-thread-3":
  waiting for ownable synchronizer 0x25452868, (a java.util.concurrent.locl
```

Lab 1 Exercise

Deadlock resolution by global ordering

Lab1 Exercise Lab1/readme.txt

- Go to DeadlockLabJavaOne2012/lab1 directory
- Run Main class to trigger deadlock (run.bat)
  - You might need a few runs
- Capture a stack trace with JVisualVM
- Verify the deadlock involves the left and right locks
- Now it is time to look at the source code
  - Source code is at src/main/java/eu/javaspecialists/deadlock/lab1
- Define a global ordering for the locks that would prevent deadlock
  - We are synchronizing on the Krasi objects
  - Define a global ordering for Krasi objects by implementing Comparable and providing a unique number to sort on (Krasi.java)
  - Change the code to use the global ordering (Thinker.java)
- Verify that the deadlock has now disappeared

Lab1 Exercise Solution Explanation

- **Goal: Prevent all philosophers from holding a single cup**

Lab1 Exercise Solution Explanation

- **Goal: Prevent all philosophers from holding a single cup**

Thinker	Cup 1 right	Cup 2 left
1	1	2
2	2	3
3	3	4
4	4	5
5	5	1

→

Thinker	Cup 1 big	Cup 2 small
1	2	1
2	3	2
3	4	3
4	5	4
5	5	1

- **The set of first cups is 2,3,4,5**
  - **This means that at most four philosophers can hold a single cup!**

Lab 2: Deadlock Resolution By TryLock

Avoiding Liveness Hazards

Lab 2: Deadlock Resolution By TryLock

- Same problem as in Lab 1
- But our solution will be different
- Instead of a global order on the locks
  - We lock the first lock
  - We then try to lock the second lock
    - If we can lock it, we start drinking
    - If we cannot, we back out completely and try again
      - What about starvation or livelock?

Lock And ReentrantLock

- **The Lock interface offers different ways of locking:**
  - **Unconditional, polled, timed and interruptible**

```
public interface Lock {
  void lock();
  void lockInterruptibly() throws InterruptedException;
  boolean tryLock();
  boolean tryLock(long timeout, TimeUnit unit)
    throws InterruptedException;
  void unlock();
  Condition newCondition();
}
```

- **Lock implementations must have same memory-visibility semantics as intrinsic locks (synchronized)**

ReentrantLock Implementation

- Like synchronized, it offers reentrant locking semantics
- Also, we can interrupt threads that are waiting for locks
  - Actually, the ReentrantLock never causes the thread to be BLOCKED, but always WAITING
  - If we try to acquire a lock unconditionally, interrupting the thread will simply go back into the WAITING state
    - Once the lock has been granted, the thread interrupts itself

Using The Explicit Lock

- **We have to call unlock() in a finally block**
  - **Every time, without exception**
  - **There are FindBugs detectors that will look for forgotten "unlocks"**

```
private final Lock lock = new ReentrantLock();

public void update() {
  lock.lock(); // this should be before try
  try {
    // update object state
    // catch exceptions and restore
    // invariants if necessary
  } finally {
    lock.unlock();
  }
}
```

Polled Lock Acquisition

- **Instead of unconditional lock, we can tryLock()**

```
if (lock.tryLock()) {
  try {
    balance = balance + amount;
  } finally {
    lock.unlock();
  }
} else {
  // alternative path
}
```

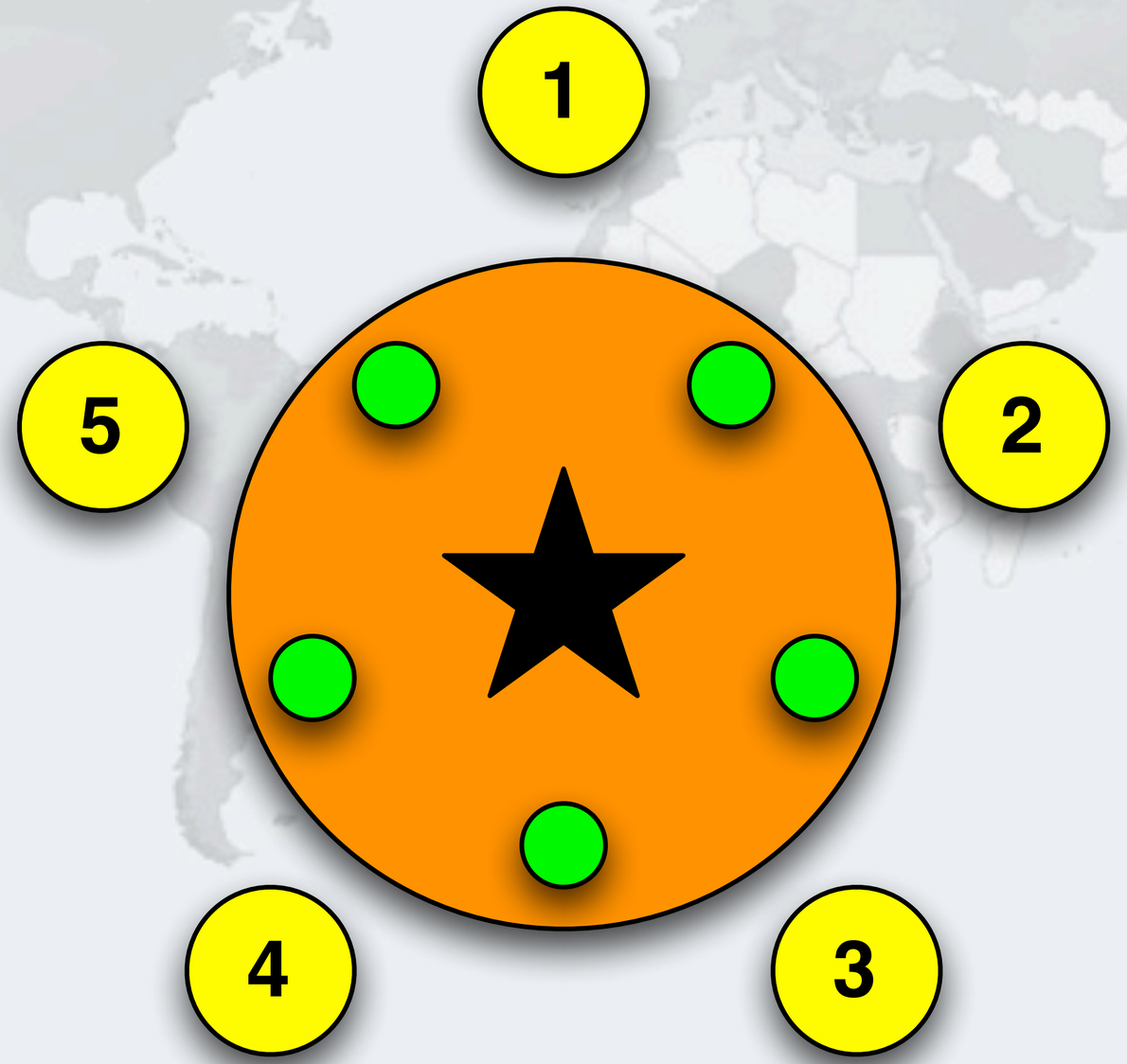
Using Try-Lock To Avoid Deadlocks

- Deadlocks happen when we lock multiple locks in different orders
- We can avoid this by using tryLock()
  - If we do not get lock, sleep for a random time and then try again
  - Must release *all* held locks, or our deadlocks become livelocks
- This is possible with synchronized, see my newsletter
  - http://www.javaspecialists.eu/archive/Issue194.html

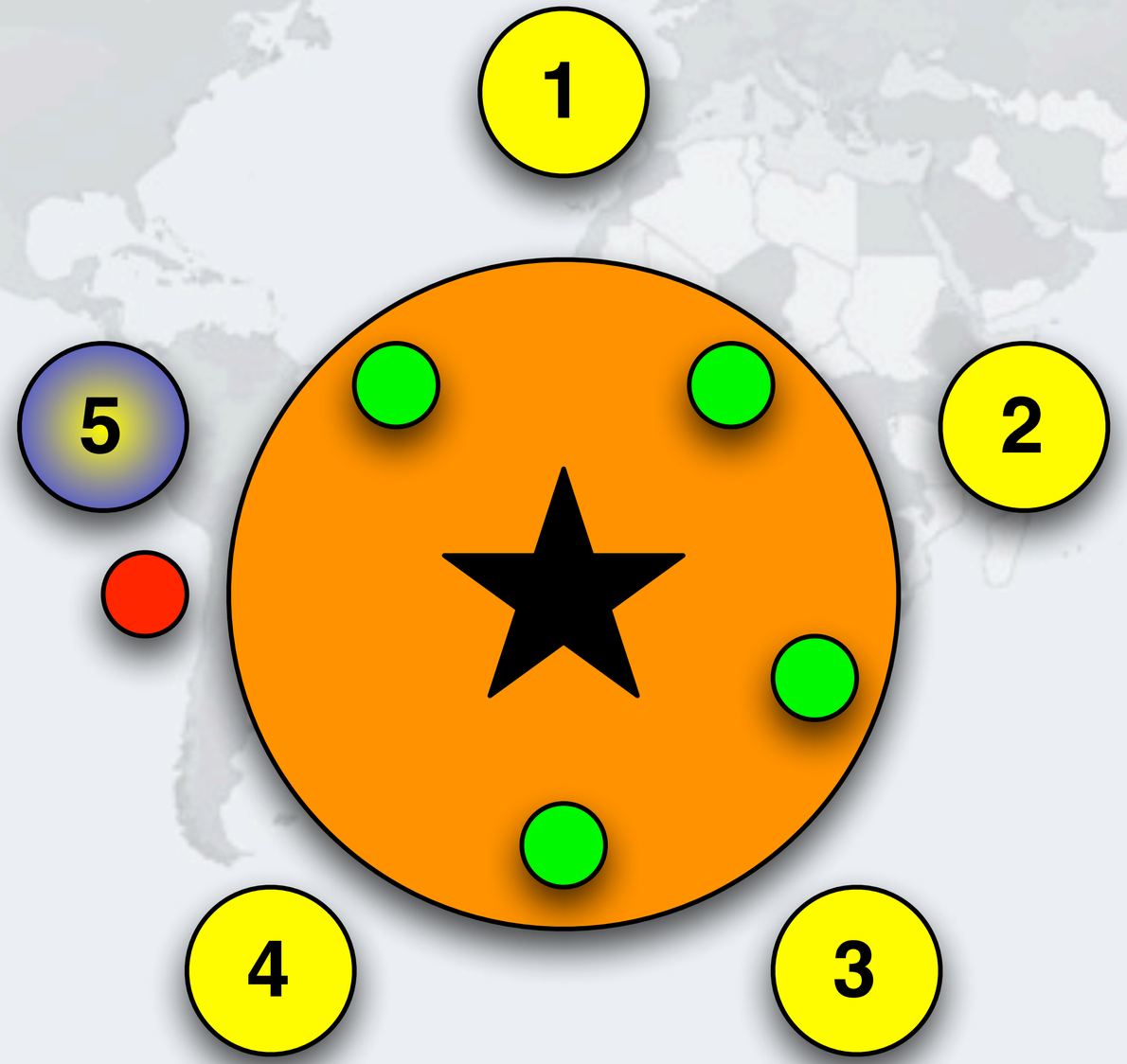
Using TryLock() To Avoid Deadlocks

```
public void drink() {
  while (true) {
    right.lock();
    try {
      if (left.tryLock()) {
        try {
          // now we can finally drink and then return
          return;
        } finally {
          left.unlock();
        }
      }
    } finally {
      right.unlock();
    }
    // sleep for a random time
  }
}
```

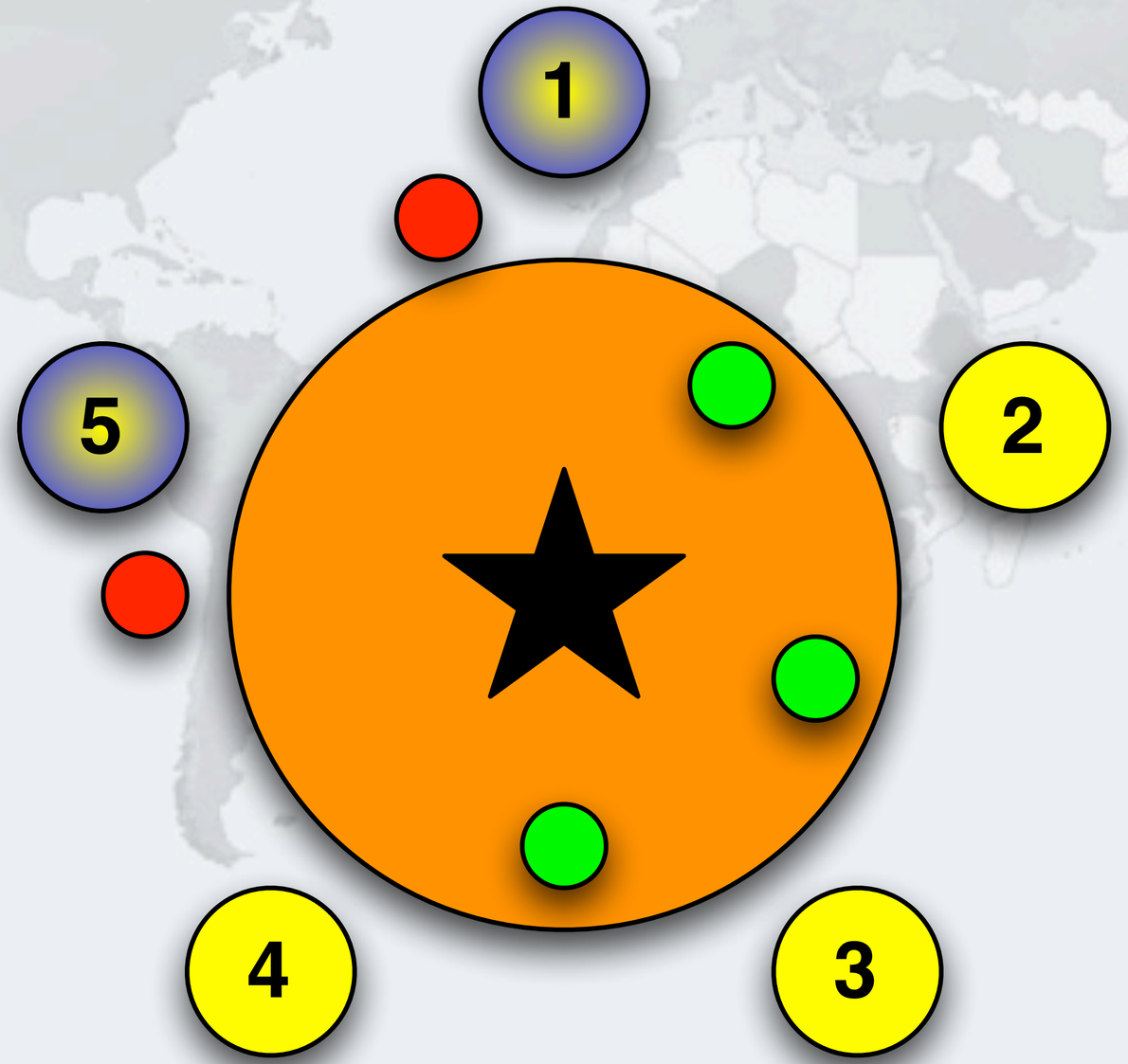
Deadlock Is Prevented In This Design



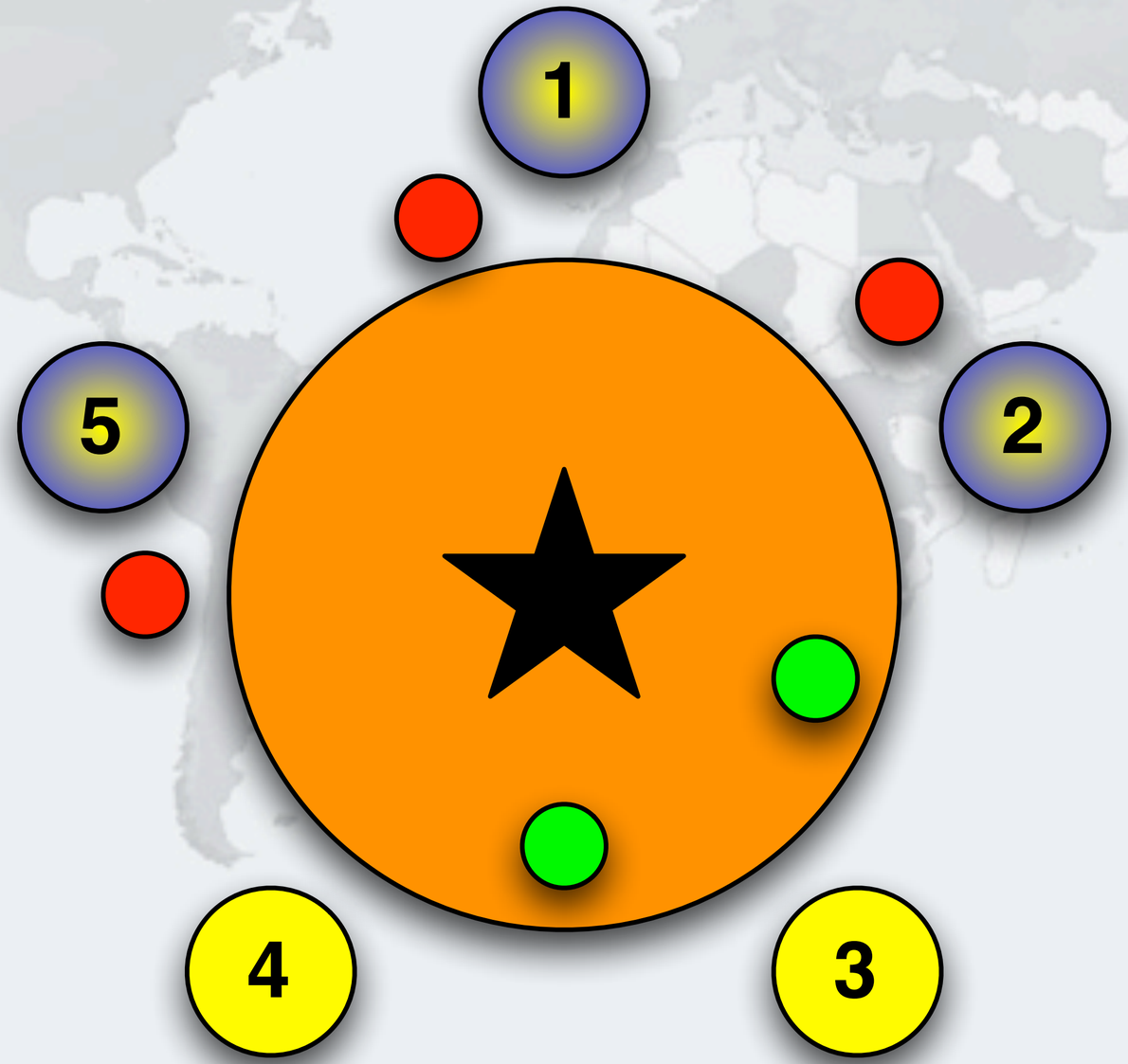
Philosopher 5 Wants To Drink, Takes Right Cup



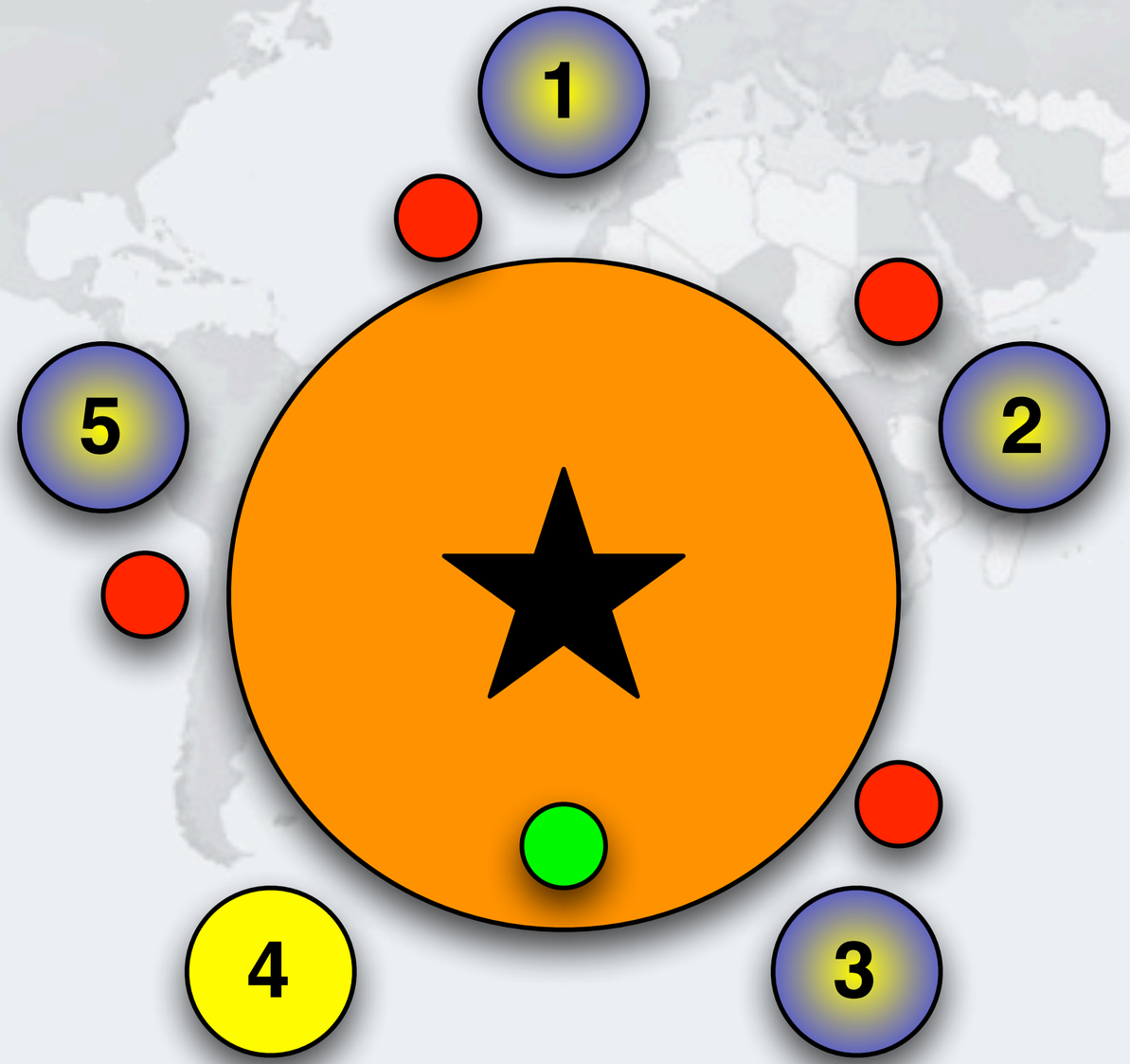
Philosopher 1 Wants To Drink, Takes Right Cup



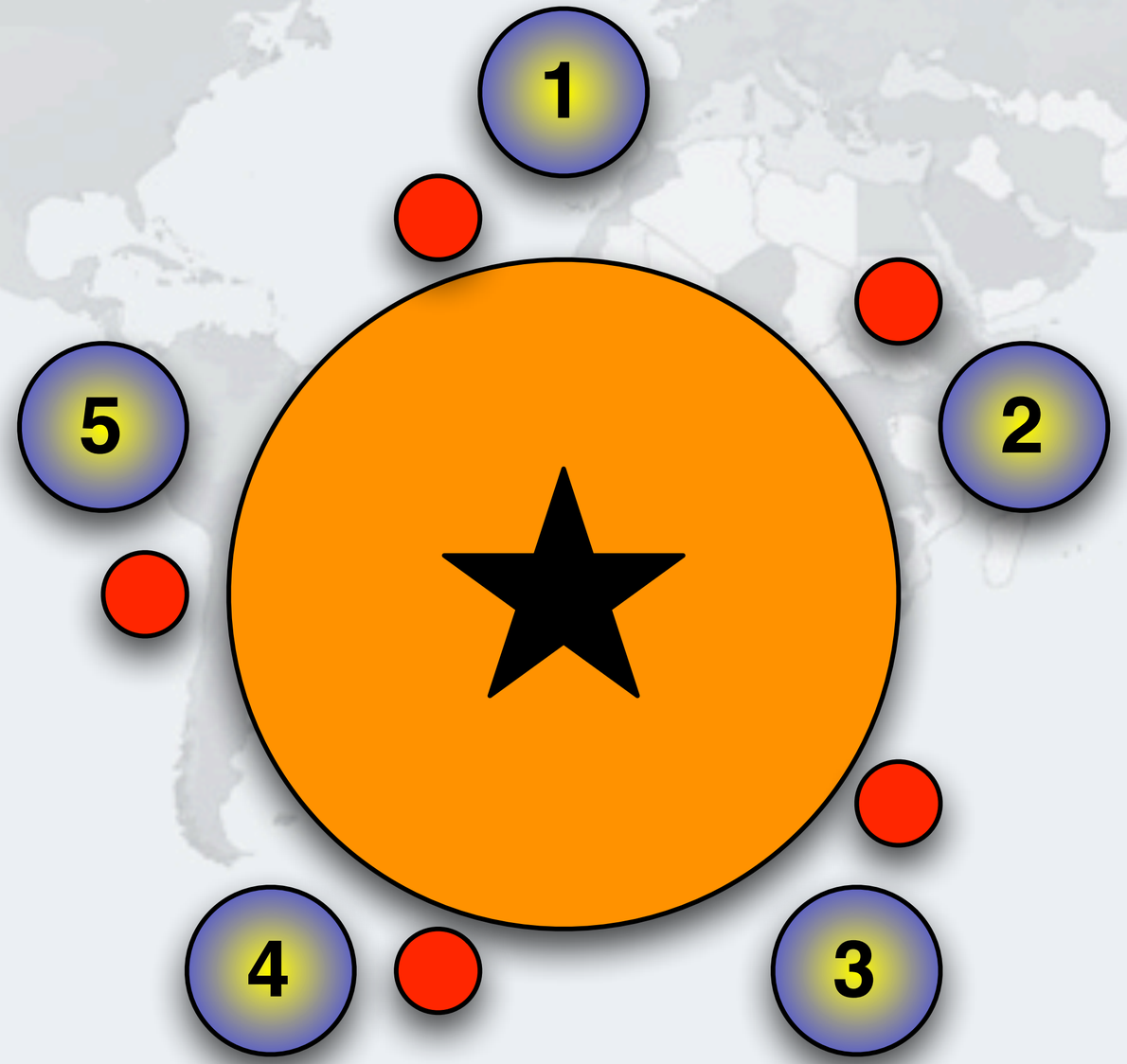
Philosopher 2 Wants To Drink, Takes Right Cup



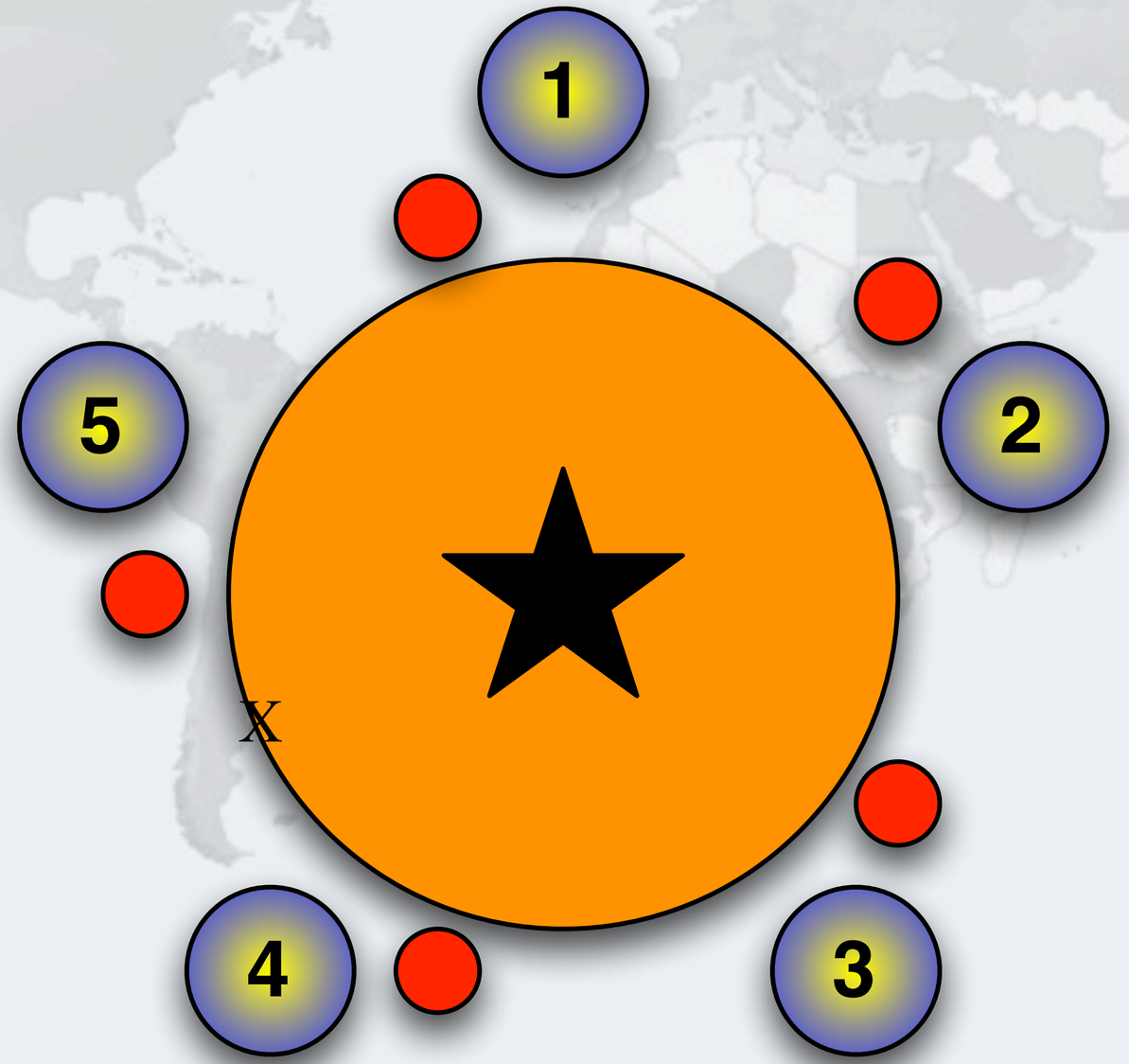
Philosopher 3 Wants To Drink, Takes Right Cup



Philosopher 4 Wants To Drink, Takes Right Cup

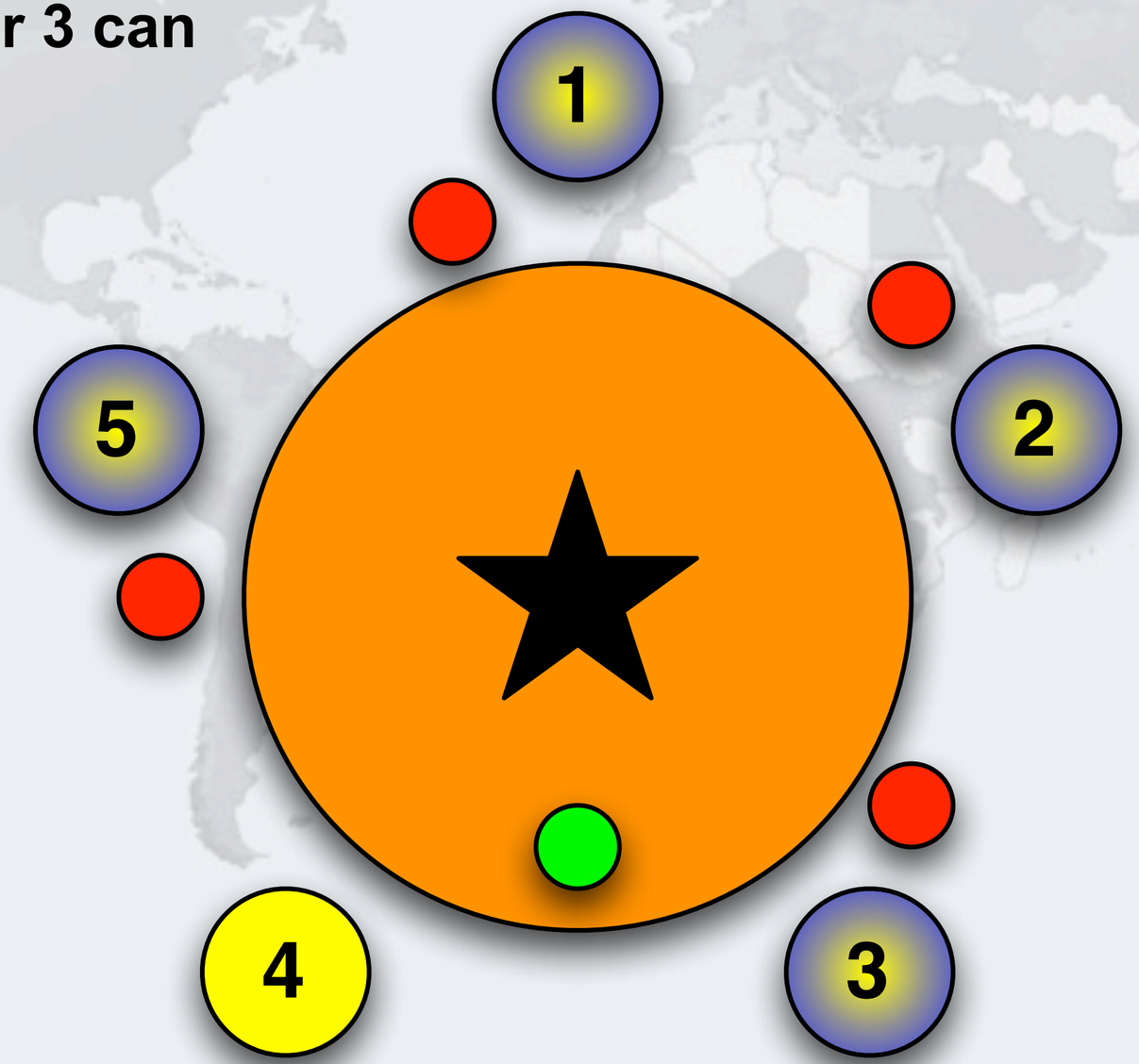


Philosopher 4 Tries To Lock Left, Not Available



Philosopher 4 Unlocks Right Again

- **Now Philosopher 3 can drink**



Lab 2 Exercise

Deadlock resolution by tryLock

Lab2 Exercise Lab2/readme.txt

- Run Main class to trigger deadlock
  - You might need a few runs
- Capture a stack trace with JVisualVM
- Verify the deadlock involves the left and right locks
- Use Lock.tryLock() to avoid blocking on the inner lock (forever)
  - lock the right
  - tryLock the left
    - if success, then drink and unlock both
    - otherwise, unlock right and retry
  - Change the Thinker.java file
- Verify that the deadlock has now disappeared

Lab2 Exercise Solution Explanation

- **Goal: Prevent all philosophers from forever blocking on the second cup**
  - **A philosopher should not die of thirst**
    - **We need to avoid livelocks**
    - **lock/tryLock vs. tryLock/tryLock**

Lab 3: Resource Deadlock

Avoiding Liveness Hazards

Lab 3: Resource Deadlock

- **Problem: threads are blocked waiting for a finite resource that never becomes available**
- **Examples:**
  - **Resources not being released after use**
    - **Running out of threads**
    - **Java Semaphores not being released**
  - **JDBC transactions getting stuck**
  - **Bounded queues or thread pools getting jammed up**
- **Challenge:**
  - **Does not show up as a Java thread deadlock**
  - **Problem thread could be in any state: RUNNING, WAITING, BLOCKED**

How To Solve Resource Deadlocks

- **Approach: If you can reproduce the resource deadlock**
  - **Take a thread snapshot shortly before the deadlock**
  - **Take another snapshot after the deadlock**
  - **Compare the two snapshots**
- **Approach: If you are already deadlocked**
  - **Take a few thread snapshots and look for threads that do not move**
- **It is useful to identify the resource that is being exhausted**
  - **A good trick is via phantom references (beyond scope of this lab)**

Resource Deadlocks

- We can also cause deadlocks waiting for resources
- For example, say you have two DB connection pools
  - Some tasks might require connections to both databases
  - Thus thread A might hold semaphore for D1 and wait for D2, whereas thread B might hold semaphore for D2 and be waiting for D1
- Thread dump and ThreadMXBean does not show this as a deadlock!

Our DatabasePool - Connect() And Disconnect()

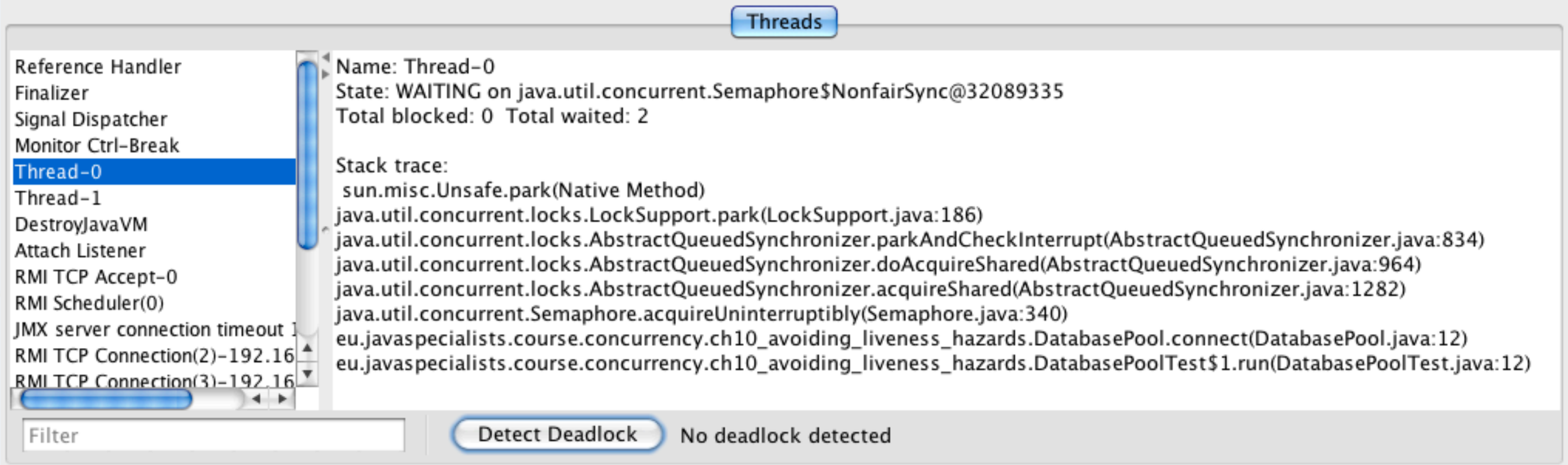
```
public class DatabasePool {
  private final Semaphore connections;
  public DatabasePool(int connections) {
    this.connections = new Semaphore(connections);
  }

  public void connect() {
    connections.acquireUninterruptibly();
    System.out.println("DatabasePool.connect");
  }

  public void disconnect() {
    System.out.println("DatabasePool.disconnect");
    connections.release();
  }
}
```

ThreadMXBean Does Not Detect This Deadlock

```
DatabasePool.connect
DatabasePool.connect
```



ThreadMXBean Does Not Detect This Deadlock

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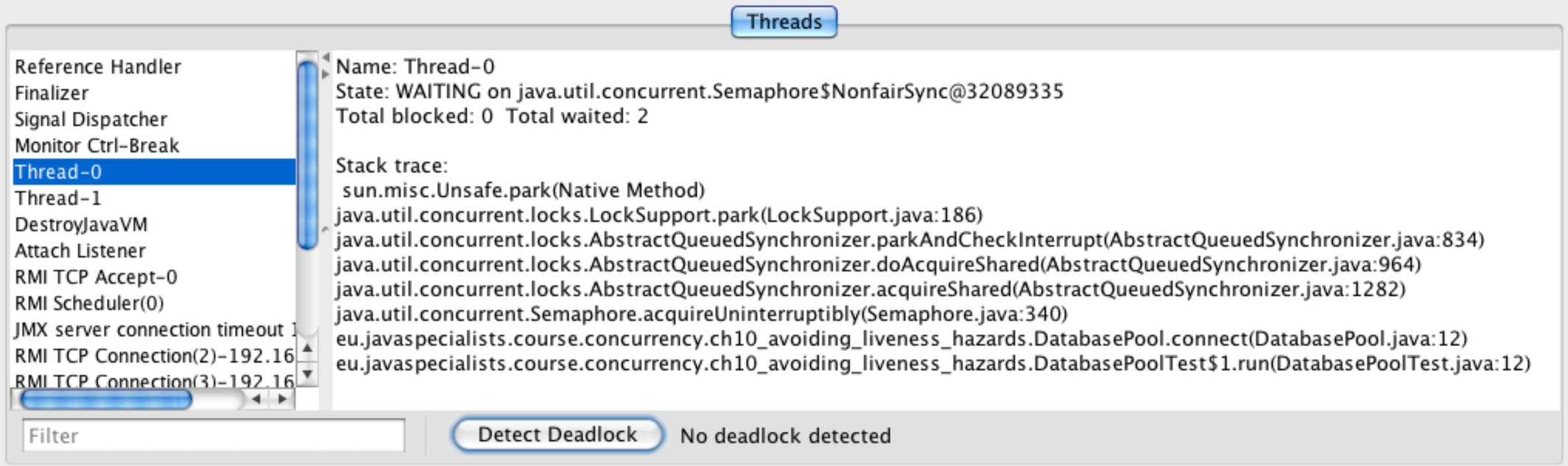
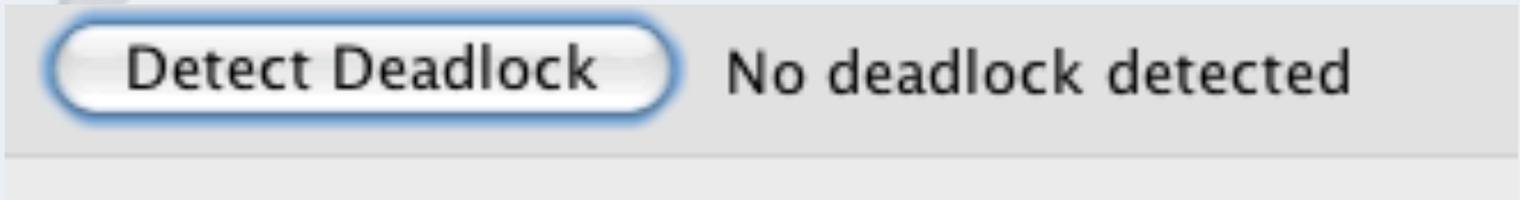




Stack Trace Gives A Vector Into The Code

```
locks.AbstractQueuedSynchronizer.doAcquireShared(AbstractQueuedSynchronizer.java:964)
locks.AbstractQueuedSynchronizer.acquireShared(AbstractQueuedSynchronizer.java:1282)
Semaphore.acquireUninterruptibly(Semaphore.java:340)
ourse.concurrency.ch10_avoiding_liveness_hazards.DatabasePool.connect(DatabasePool.java:12)
```

```
public class DatabasePool {
  // ...

  public void connect() {
    connections.acquireUninterruptibly(); // line 12
    System.out.println("DatabasePool.connect");
  }
}
```

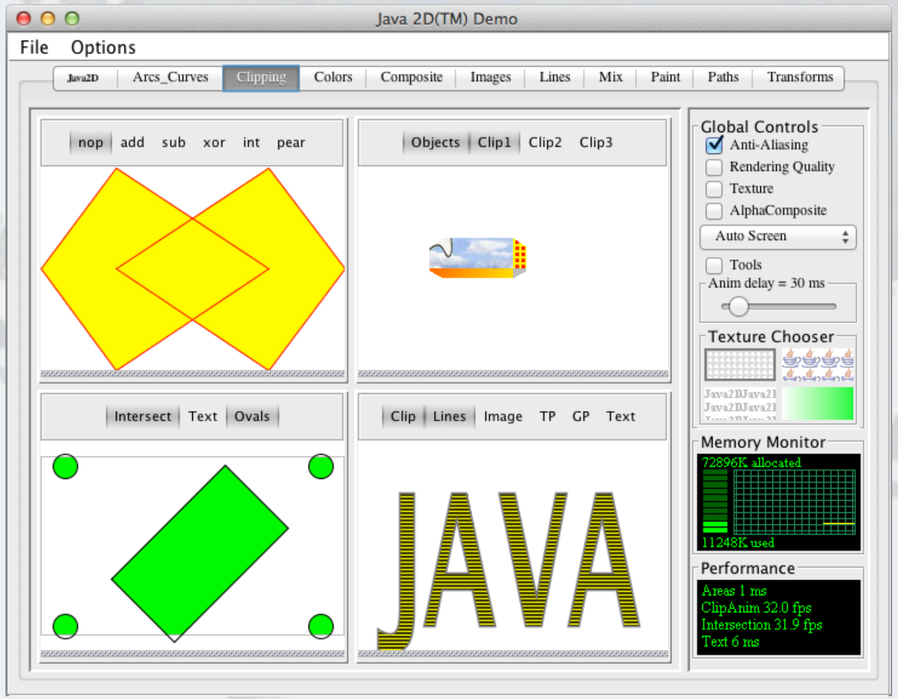
Lab 3 Exercise

Resource Deadlock

Javaspecialists.eu
java training

Lab3 Exercise Lab3/readme.txt

- Start our modified Java2Demo
- Connect JVisualVM and dump all threads
- Use Java2Demo for a while until it deadlocks
- Get another thread dump and compare to the first one
  - This should show you where the problem is inside your code
- Fix the problem and verify that it has been solved
  - Hint: Your colleagues probably write code like this, but you shouldn't



Lab3 Exercise Solution Explanation

- **Goal: Ensure that resources are released after use**
- **Diff between the two thread dumps using jps and jstack**

< at java.util.concurrent.locks.AbstractQueuedSynchronizer$ConditionObject.await(AbstractQueuedSynchronizer.java:2043)
< at java.awt.EventQueue.getNextEvent(EventQueue.java:531)
< at java.awt.EventDispatchThread.pumpOneEventForFilters(EventDispatchThread.java:213)

> at java.util.concurrent.locks.AbstractQueuedSynchronizer.parkAndCheckInterrupt(AbstractQueuedSynchronizer.java:834)
> at java.util.concurrent.locks.AbstractQueuedSynchronizer.doAcquireSharedInterruptibly(AbstractQueuedSynchronizer.java:994)
> at java.util.concurrent.locks.AbstractQueuedSynchronizer.acquireSharedInterruptibly(AbstractQueuedSynchronizer.java:1303)
> at java.util.concurrent.Semaphore.acquire(Semaphore.java:317)
> at eu.javaspecialists.deadlock.lab3.java2d.MemoryManager.gc(MemoryManager.java:56)
> at eu.javaspecialists.deadlock.lab3.java2d.MemoryMonitor$Surface.paint(MemoryMonitor.java:153)

  - **Most likely the fault will be in one of our classes, rather than the JDK**

What Is Wrong With This Code?

```
/**
 * Only allow a maximum of 30 threads to call System.gc() at a time.
 */
public class MemoryManager extends Semaphore {
  private static final int MAXIMUM_NUMBER_OF_CONCURRENT_GC_CALLS = 30;

  public MemoryManager() {
    super(MAXIMUM_NUMBER_OF_CONCURRENT_GC_CALLS);
  }

  public void gc() {
    try {
      acquire();
      try {
        System.gc();
      } finally {
        System.out.println("System.gc() called");
        release();
      }
    } catch (Exception ex) {
      // ignore the InterruptedException
    }
  }
}
```

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Calling System.gc() is baddd (but not **the** problem)

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```

Calling System.gc() is baddd (but not **the** problem)

Empty catch block hides problem

Wrap Up

Avoiding Liveness Hazards

Conclusion On Deadlocks

- Concurrency is difficult, but there are tools and techniques that we can use to solve problems
- These are just a few that we use
- For more information, have a look at
  - The Java Specialists' Newsletter - http://www.javaspecialists.eu
- We have helped a lot of companies by training their Java programmers
  - Java Concurrency
  - Java Performance Tuning
  - Java Design Patterns
  - Advanced Java Techniques (Java NIO, threading, data structs, etc.

And One More Thing

- **We have prepared a fourth lab for you to do at home**
  - **Either take it along with a memory stick or get it from**
    - **https://github.com/kabutz/DeadlockLabJavaOne2012.git**
  - **Send questions and comments to heinz@kabutz.net**

Questions?

heinz@kabutz.net

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