

Static Deadlock Detection for Java Libraries

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Deadlock

- Each deadlocked thread attempts to acquire a lock held by another thread
 - Can halt entire program execution
 - Difficult to expose during testing
 - Once exposed, difficult to replicate
- Example:

StringBuffer *a*, *b*;

Thread 1:

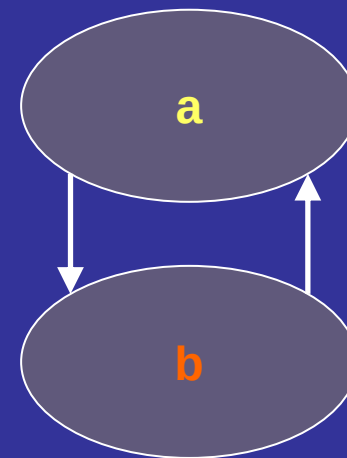
a.append(*b*);

locks *a*, *b*

Thread 2:

b.append(*a*);

locks *b*, *a*



Deadlock in Libraries

- Library writers may wish to provide guarantees
 - JDK's StringBuffer documentation says class is thread-safe
- Goal: find client calls that deadlock library or verify that none exist

Analyzing Programs / Libraries

	For Programs:	For Libraries:
Method Calls	Fixed	Consider all calling patterns
Aliasing Possibilities	Fixed	Consider aliasing induced by any program
Number of Threads	Might be known	Unbounded

Deadlock from Sun's JDK

```
import java.beans.beancontext.*;
```

```
BeanContextSupport support = new BeanContextSupport();
```

```
Object source = new Object();
```

```
PropertyChangeEvent event =
```

```
    new PropertyChangeEvent(source, "beanContext", ...);
```

```
support.add(source);
```

```
support.vetoableChange(event);
```

Thread 1:

```
support.propertyChange(event);
```

*locks **global**, **field***

Thread 2:

```
support.remove(source);
```

*locks **field**, **global***

Also found 13 other deadlocks

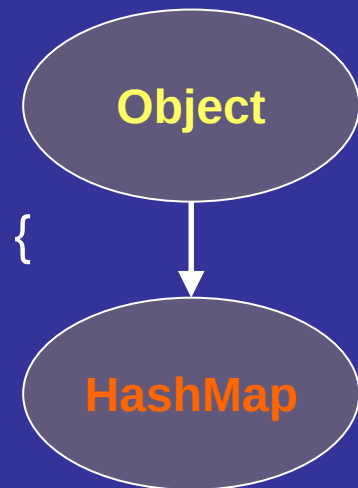
Analysis Overview

1. Build lock-order graph representing locking behavior of each method in library
2. Combine graphs for all public methods into single graph
3. Detect cycles in this graph, which indicate deadlock possibilities
 - Analysis properties: reports all deadlocks, context-sensitive, flow-sensitive

JDK Source (simplified)

```
interface BeanContext {  
    public static final Object globalHierarchyLock;  
}  
class BeanContextSupport {  
    protected HashMap children;  
  
    public boolean remove(Object targetChild) {  
        synchronized(BeanContext.globalHierarchyLock) {  
            ...  
            synchronized(children) {  
                children.remove(targetChild);  
            }  
            ...  
        }  
        ...  
    }  
}
```

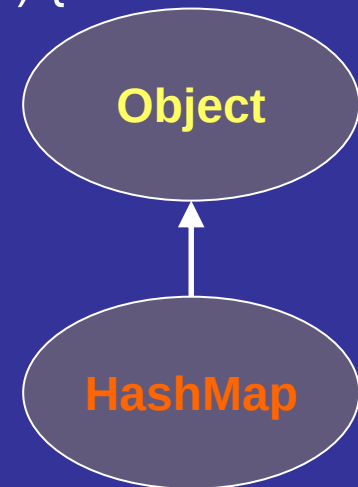
Continued...



JDK Source (simplified), cont.

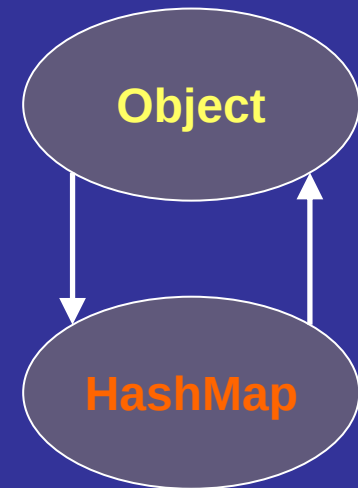
```
class BeanContextSupport {  
    protected HashMap children;  
    public void propertyChange(PropertyChangeEvent pce) {  
        ...  
        Object source = pce.getSource();  
        synchronized(children) {  
            if (...) {  
                ...  
                remove(source);  
                ...  
            }  
        }  
    }  
}
```

```
public boolean remove(Object targetChild) {  
    synchronized (BeanContext.globalHierarchyLock) {  
        ...  
    }  
}
```



Merged Graph

- When merged, graphs indicate possible locking orders of all methods
- Cycles indicate possible deadlock
 - Expose cases in which threads lock set of locks in different (conflicting) orders



Outline

- Introduction
- **Deadlock Detection Algorithm**
- Results
- Related Work and Conclusions

Synchronization in Java

- Locking is hierarchical, performed using synchronized statement
 - Multiple locks acquired via nested synchronized statements
- Synchronizing on previously acquired lock always succeeds
 - Considered a no-op for our analysis
- Synchronized methods sugar for synchronizing on **this**

```
synchronized (lock1) {  
    synchronized (lock2) {  
        ...  
    }  
}
```

Synchronization in Java

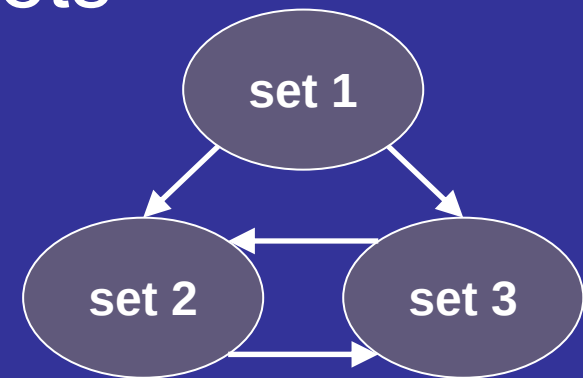
- wait() and notify() methods
- Java 1.5's non-hierarchical primitives (in `java.concurrent` package) not covered by analysis
 - Usage rare; recommended only for expert programmers

Analysis Overview

1. Build lock-order graph representing locking behavior of each method in library
 - Callee graphs integrated into caller
 - Iterate to fixed point; termination guaranteed
2. Combine graphs for all public methods into single graph
3. Detect cycles in this graph, which indicate deadlock possibilities

Lock-order Graph

- Directed graph that represents the order in which locks are acquired
- Nodes represent may-alias sets
 - Allows graphs from different methods to be combined
- Edges mean the source lock held while destination lock acquired
- Cycles indicate possibility of deadlock



Example Library

```
public void deposit(Bank b1,  
                    Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
public void openAccount(Bank b2,  
                        Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Example Analysis: deposit()

```
public void deposit(Bank b1,
                   Client c1) {
    synchronized (b1) {
        synchronized (c1) {
            ...
        }
    }
}

public void openAccount(Bank b2,
                       Client c2) {
    synchronized (b2) {
        ...
    }
    synchronized (c2) {
        deposit(b2, c2);
    }
}
```

Graph:

Ordered list of locks held:

[]

Example Analysis: deposit()

```
public void deposit(Bank b1,  
                    Client c1) {
```



```
    synchronized (b1) {  
        synchronized (c1) {
```

```
            ...
```

```
        }
```

```
    }
```

```
}
```

```
public void openAccount(Bank b2,  
                        Client c2) {
```

```
    synchronized (b2) {
```

```
        ...
```

```
    }
```

```
    synchronized (c2) {  
        deposit(b2, c2);
```

```
    }
```

```
}
```

Graph:

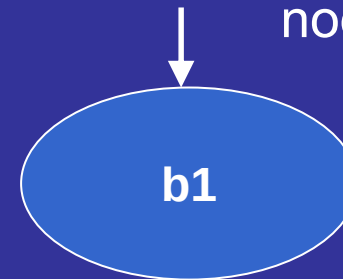
Ordered list of locks held:

[]

Example Analysis: deposit()

```
public void deposit(Bank b1,  
                    Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
public void openAccount(Bank b2,  
                        Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Graph:



No locks held, so
node is root

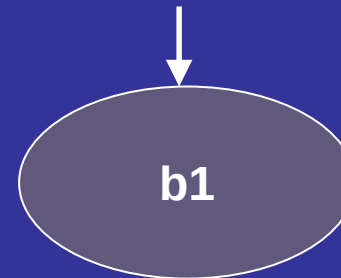
Ordered list of locks held:

[**b1**]

Example Analysis: deposit()

```
public void deposit(Bank b1,  
                    Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
public void openAccount(Bank b2,  
                        Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Graph:

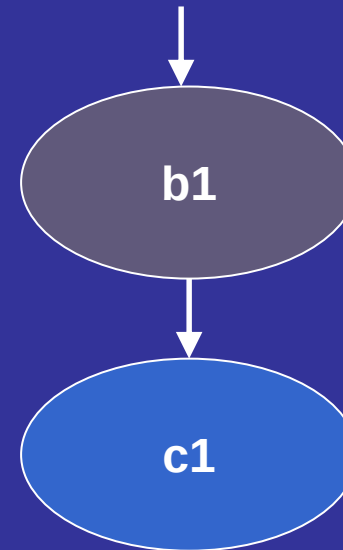


Ordered list of locks held:
[b1]

Example Analysis: deposit()

```
public void deposit(Bank b1,  
                    Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
public void openAccount(Bank b2,  
                        Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Graph:



Ordered list of locks held:

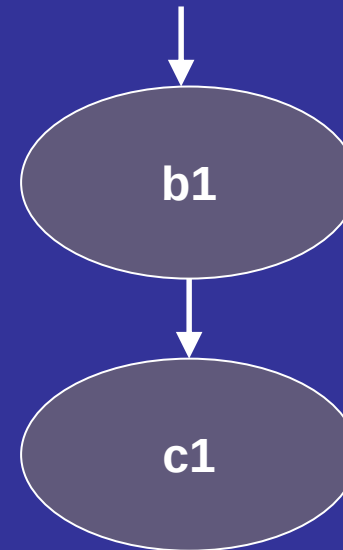
[b1, **c1**]

Example Analysis: deposit()

```
public void deposit(Bank b1,  
                    Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
public void openAccount(Bank b2,  
                        Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```



Graph:



Ordered list of locks held:

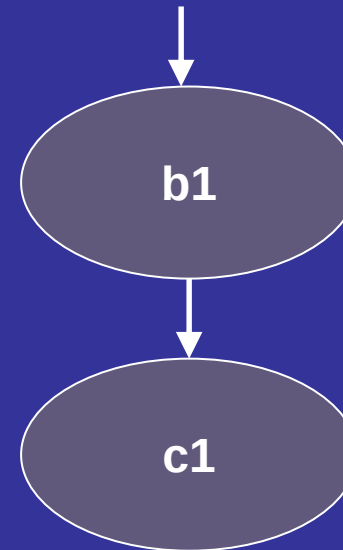
[b1, c1]

Example Analysis: deposit()

```
public void deposit(Bank b1,  
                    Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
public void openAccount(Bank b2,  
                        Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```



Graph:



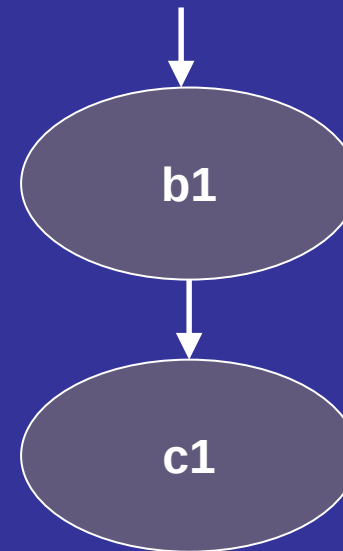
Ordered list of locks held:

[b1]

Lock-order graph for deposit()

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
→ public void openAccount(Bank b2,  
                          Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Graph:



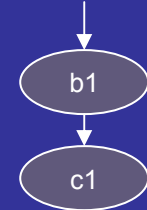
Example Analysis: openAccount()

```
public void deposit(Bank b1,
                   Client c1) {
    synchronized (b1) {
        synchronized (c1) {
            ...
        }
    }
}

public void openAccount(Bank b2,
                       Client c2) {
    synchronized (b2) {
        ...
    }
    synchronized (c2) {
        deposit(b2, c2);
    }
}
```

Graph:

deposit's graph:



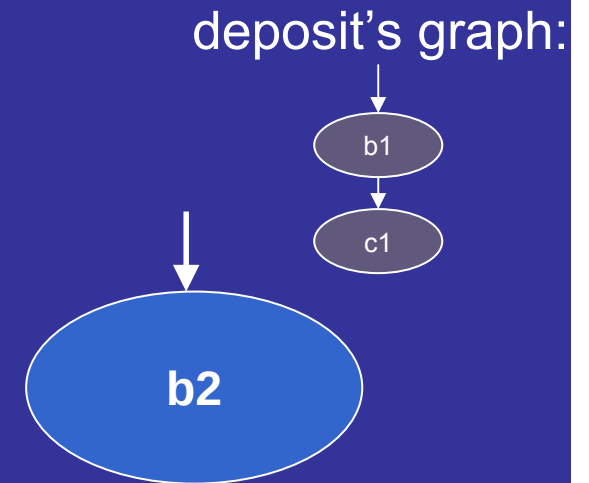
Ordered list of locks held:

[]

Example Analysis: openAccount()

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    → synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Graph:



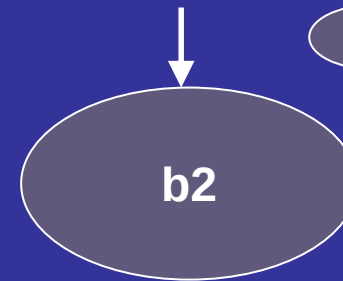
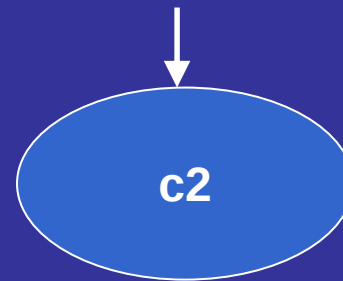
Ordered list of locks held:

[b2]

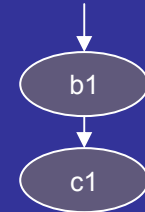
Example Analysis: openAccount()

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Graph:



deposit's graph:



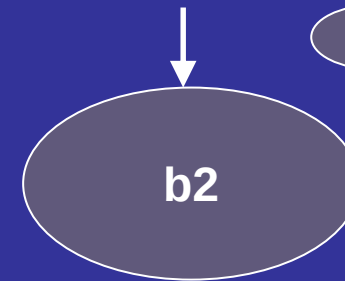
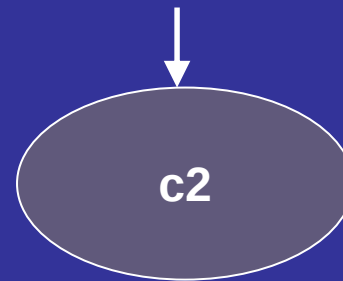
Ordered list of locks held:

[c2]

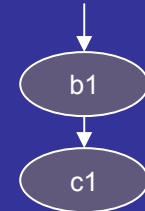
Example Analysis: openAccount()

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Graph:



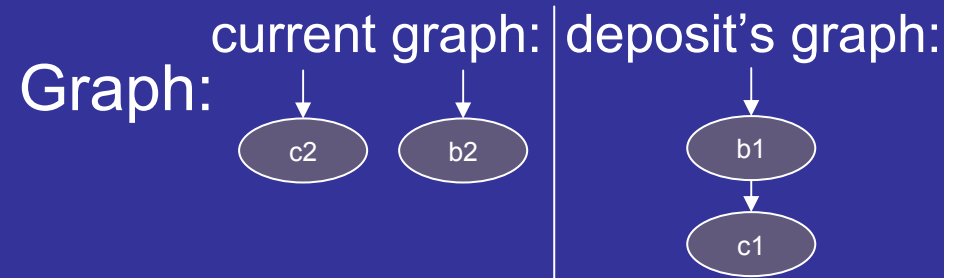
deposit's graph:



Ordered list of locks held:
[c2]

Example Analysis: openAccount()

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```



Ordered list of locks held:
[c2]

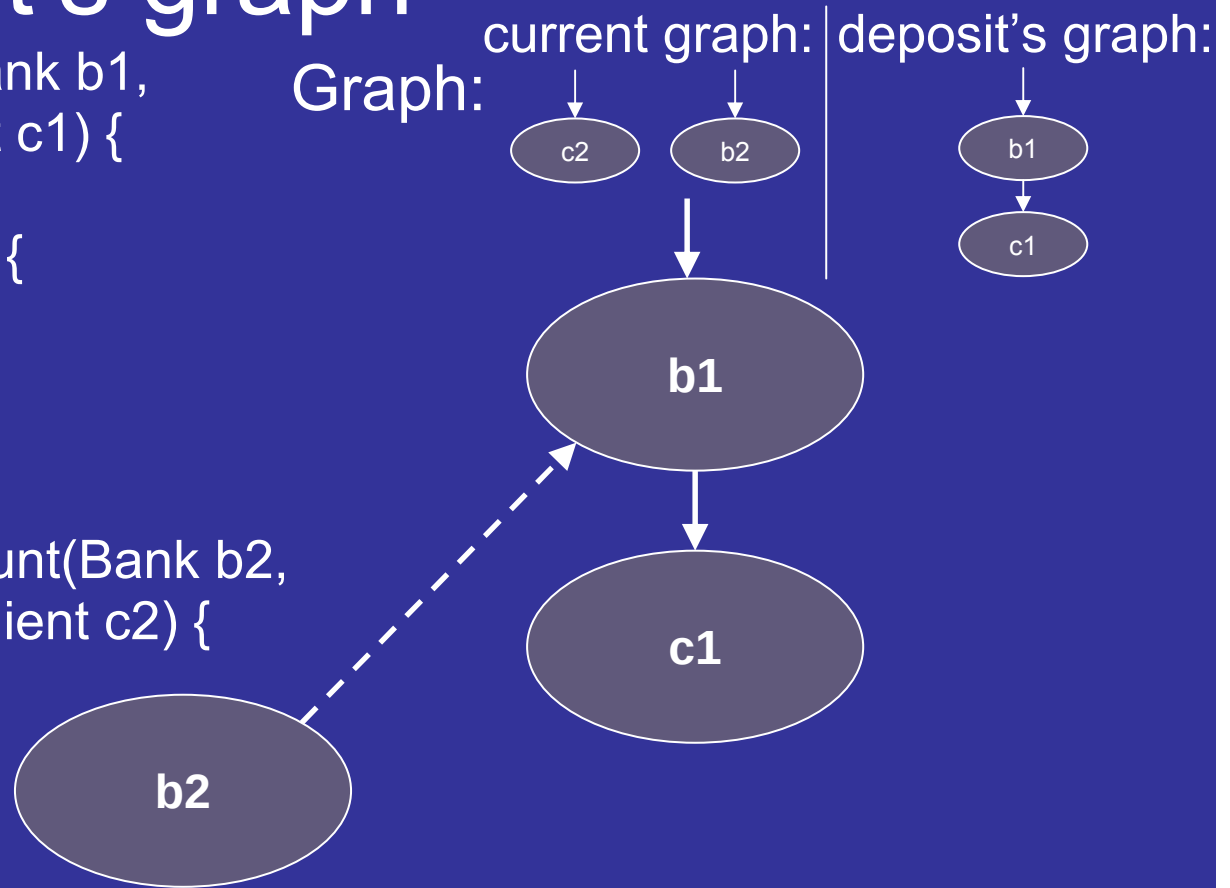
Call to deposit(): update copy of deposit's graph

```
public void deposit(Bank b1,
                   Client c1) {
    synchronized (b1) {
        synchronized (c1) {
            ...
        }
    }
}

public void openAccount(Bank b2,
                       Client c2) {
    synchronized (b2) {
        ...
    }
    synchronized (c2) {
        deposit(b2, c2);
    }
}
```



Graph:



Ordered list of locks held:
[c2]

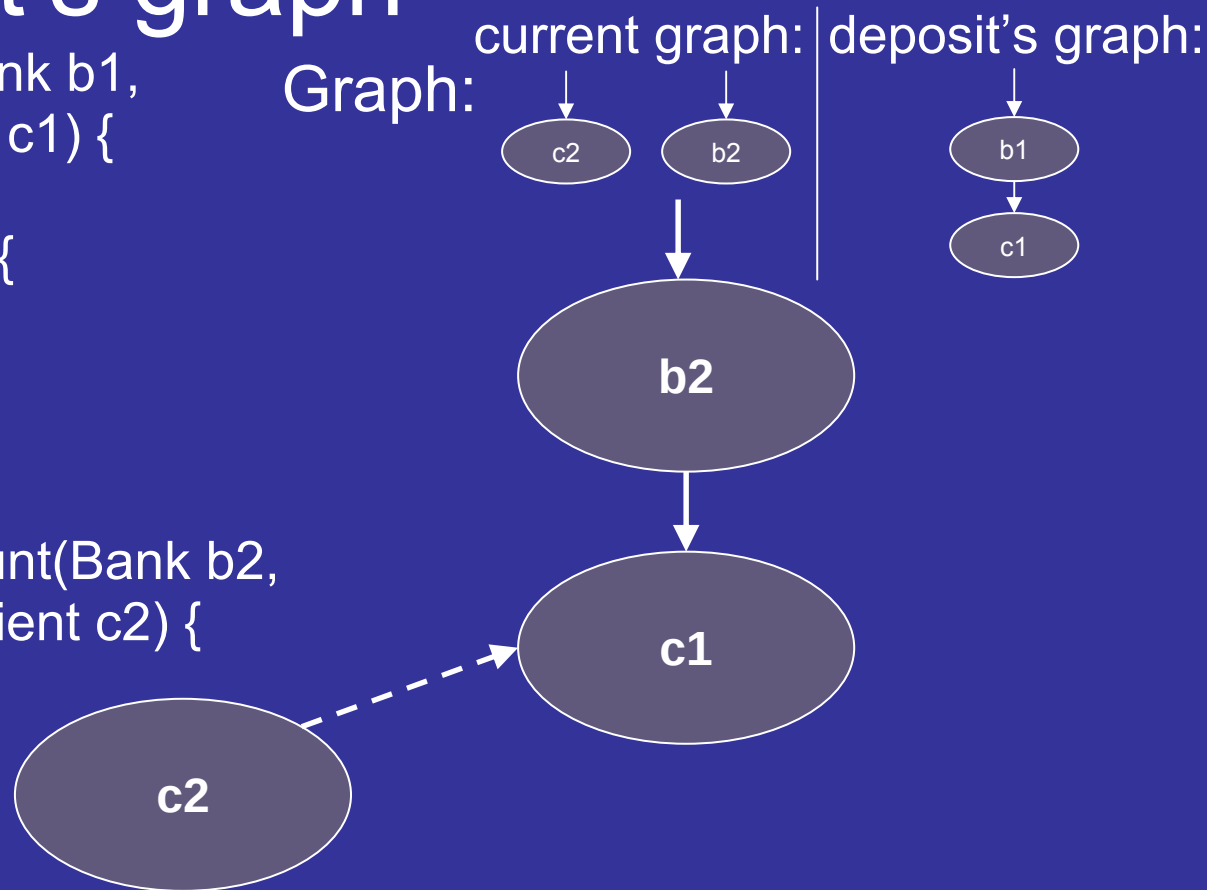
Call to deposit(): update copy of deposit's graph

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}
```

```
...  
}  
}  
}  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```



Graph:

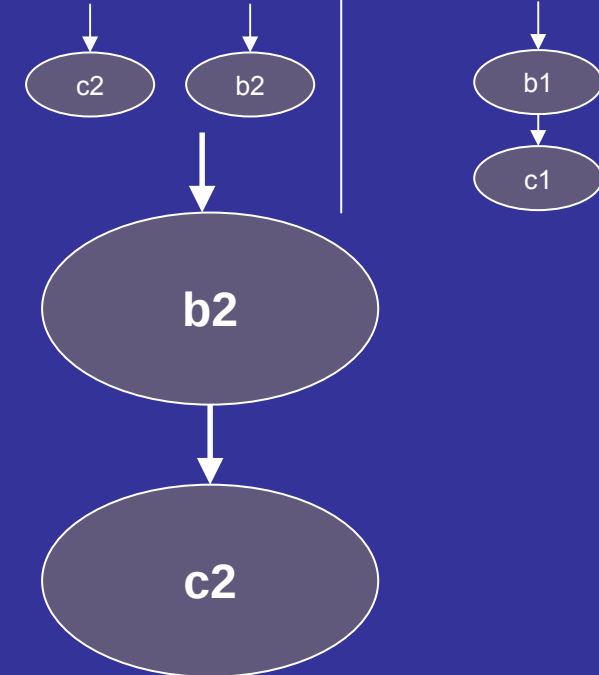


Call to deposit(): update copy of deposit's graph

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```



Graph: current graph: deposit's graph:

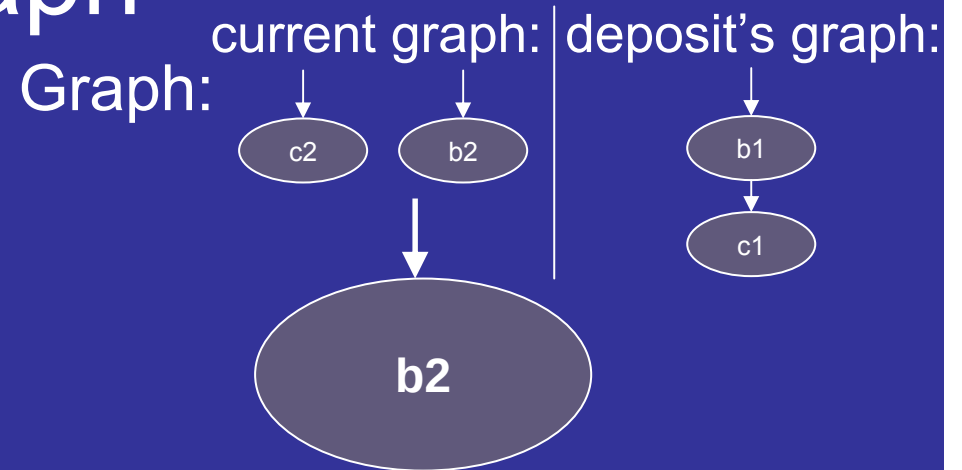


Ordered list of locks held:
[c2]

Call to deposit(): update copy of deposit's graph

```
public void deposit(Bank b1,
                   Client c1) {
    synchronized (b1) {
        synchronized (c1) {
            ...
        }
    }
}

public void openAccount(Bank b2,
                       Client c2) {
    synchronized (b2) {
        ...
    }
    synchronized (c2) {
        deposit(b2, c2);
    }
}
```



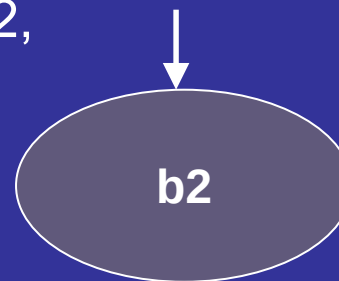
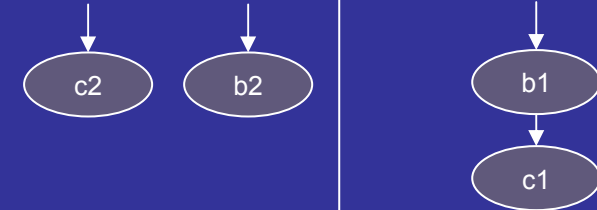
Ordered list of locks held:
[c2]

Call to deposit(): update copy of deposit's graph

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```



Graph: current graph: | deposit's graph:



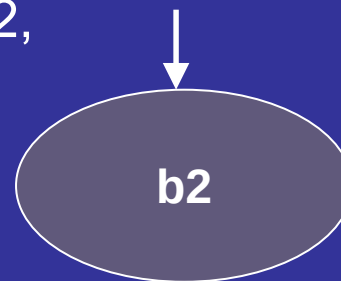
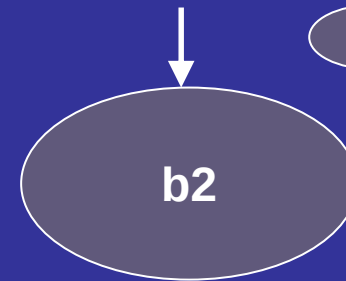
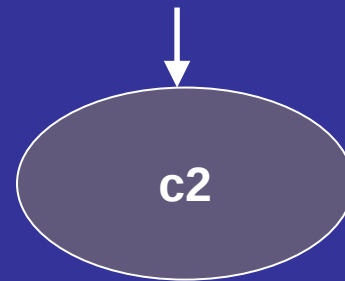
Ordered list of locks held:
[c2]

Call to deposit(): insert deposit's graph

```
public void deposit(Bank b1,  
                  Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                      Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

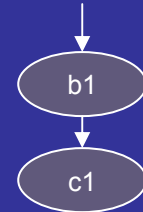


Graph:



Ordered list of locks held:
[c2]

deposit's graph:

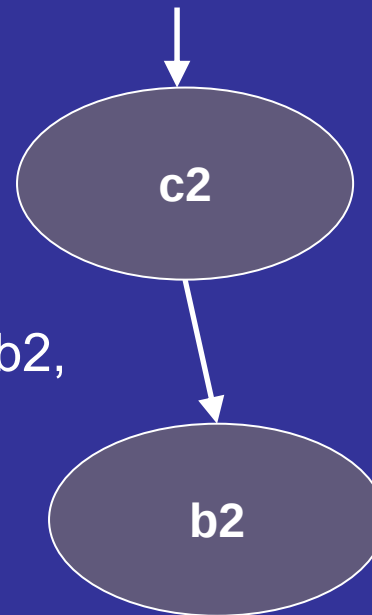


Call to deposit(): insert deposit's graph

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

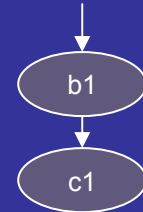


Graph:



Ordered list of locks held:
[c2]

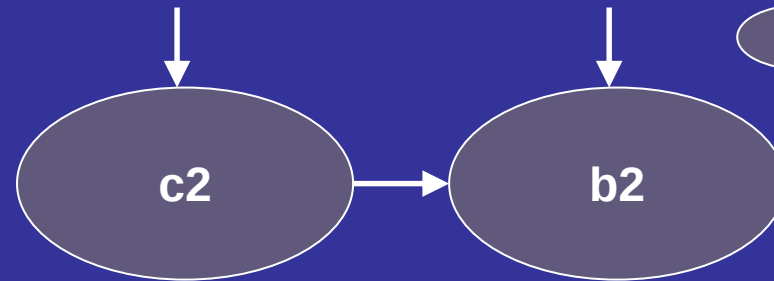
deposit's graph:



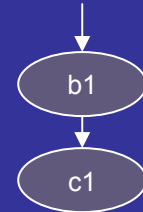
Call to deposit(): insert deposit's graph

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```

Graph:



deposit's graph:



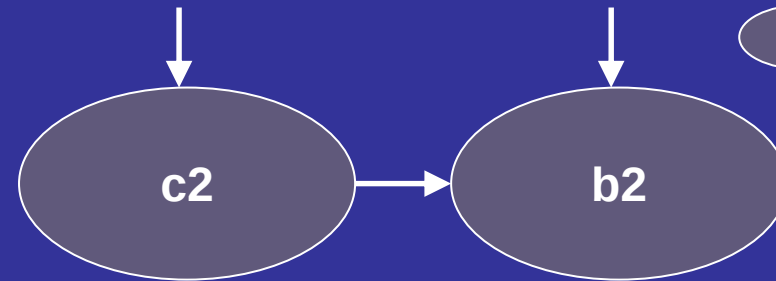
Ordered list of locks held:
[c2]

Lock-order graph for openAccount()

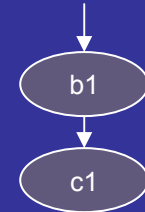
```
public void deposit(Bank b1,  
                    Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                        Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```



Graph:



deposit's graph:

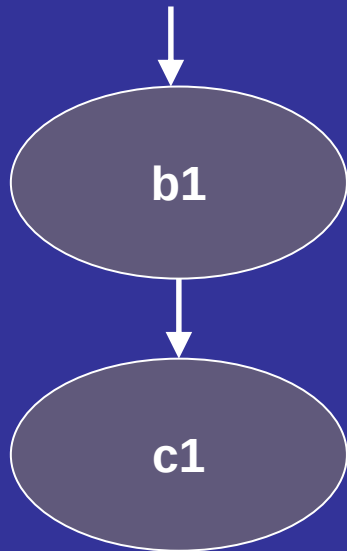


Analysis Overview

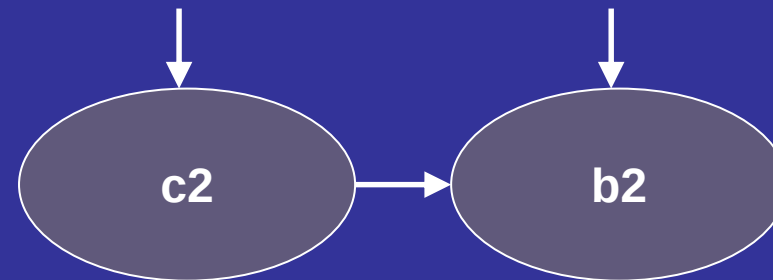
1. Build lock-order graph representing locking behavior of each method in library
 - Callee graphs integrated into caller
 - Iterate to fixed point; termination guaranteed
2. Combine graphs for all public methods into single graph
3. Detect cycles in this graph, which indicate deadlock possibilities

Combine Graphs

Graph for deposit():

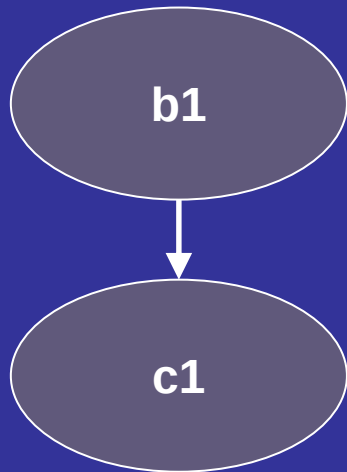


Graph for openAccount():

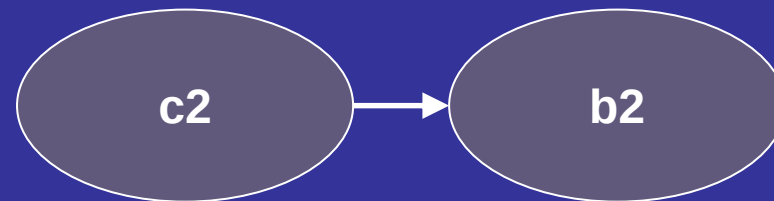


Combine Graphs

Graph for deposit():

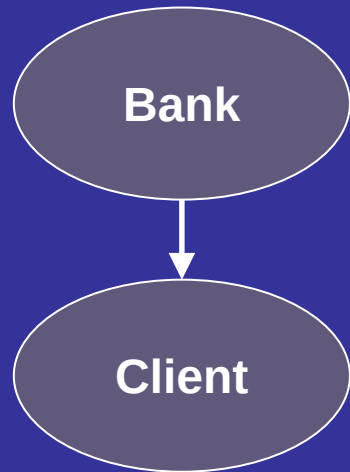


Graph for openAccount():

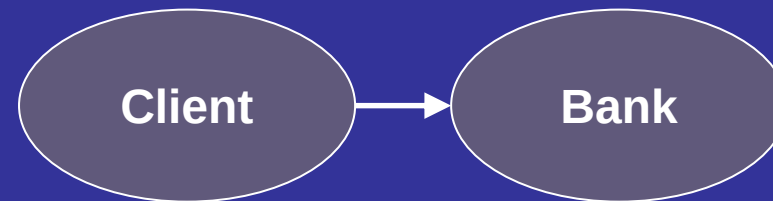


Combine Graphs

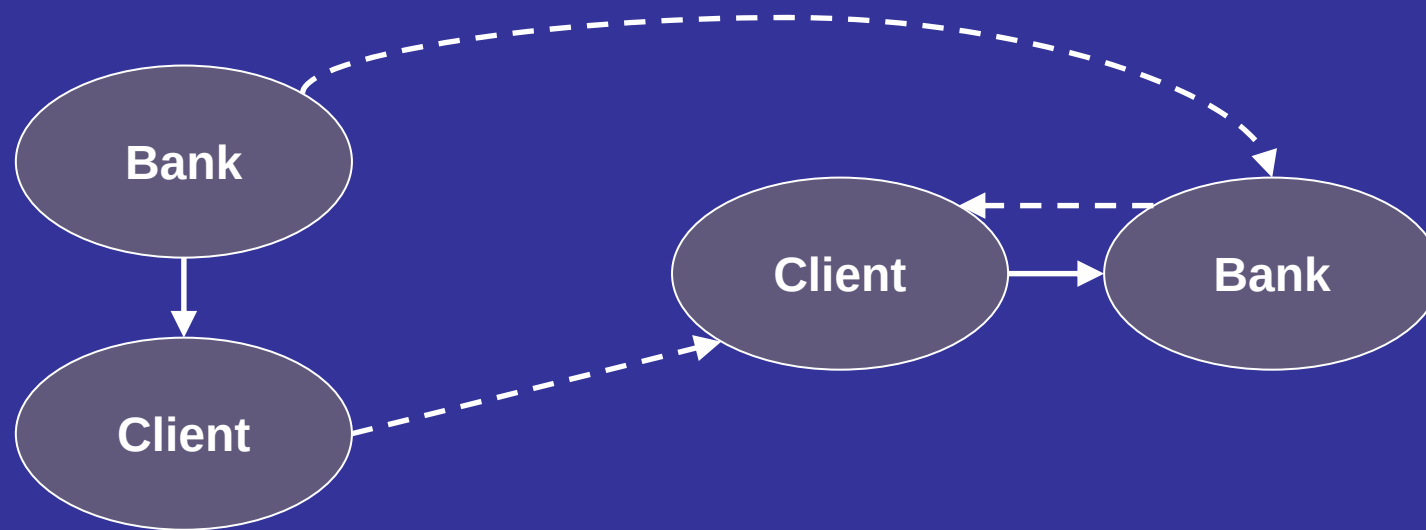
Graph for deposit():



Graph for openAccount():

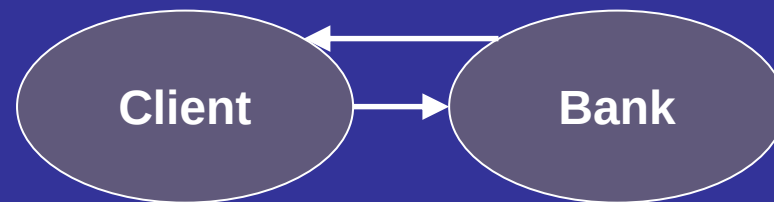


Combine Graphs



Combine Graphs

Final graph:



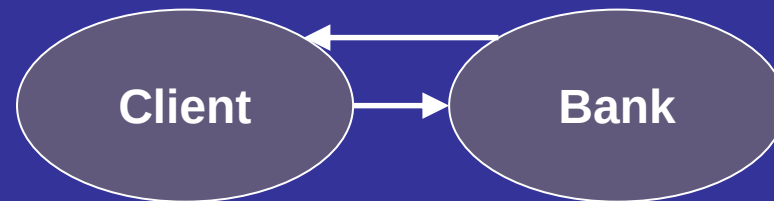
Analysis Overview

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 - Iterate to fixed point; termination guaranteed
2. Combine graphs for all public methods into single graph
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Cycle in Combined Graph

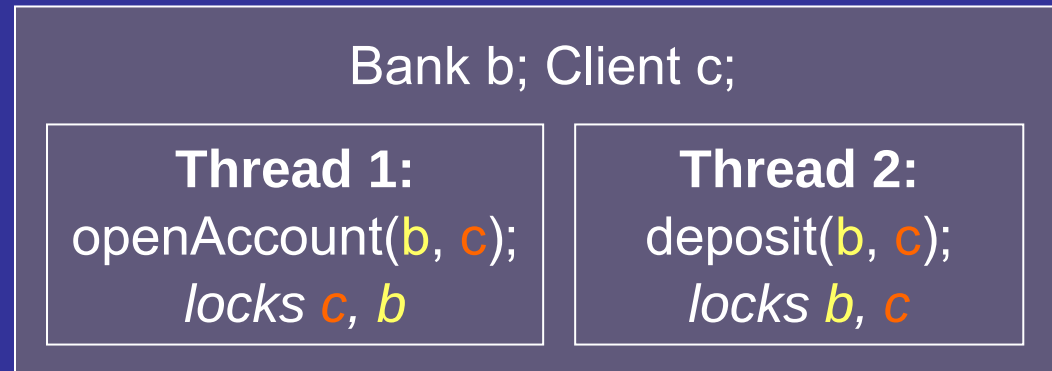
Cycles indicate
possibility of deadlock,
and deadlock is
possible

Final graph:



Code that Deadlocks Library

```
public void deposit(Bank b1,  
                   Client c1) {  
    synchronized (b1) {  
        synchronized (c1) {  
            ...  
        }  
    }  
}  
  
public void openAccount(Bank b2,  
                       Client c2) {  
    synchronized (b2) {  
        ...  
    }  
    synchronized (c2) {  
        deposit(b2, c2);  
    }  
}
```



Beyond Public Methods

- Graph for library must also include static initializers and finalizers
- Method calls to `Thread.start()` handled specially
 - Lock-order graphs for receiver's `run()` method integrated into graph for whole library
- ECOOP paper omitted these cases; addressed in forthcoming Technical Report

Handling wait() and notify()

- Calling wait() releases and later reacquires receiver's lock
 - Considered no-op if receiver's lock most recently acquired
 - Can change lock order even if receiver's lock is held

Handling wait() and notify()

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```
synchronized (a) {  
    synchronized (b) {  
        ...  
        b.wait()  
        ...  
    }  
}
```

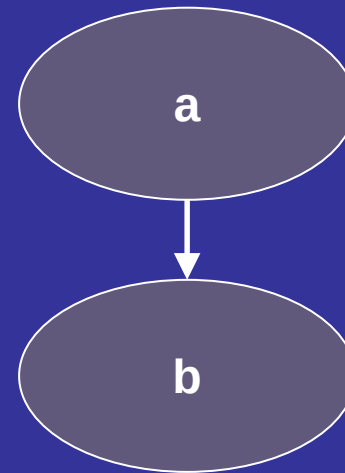


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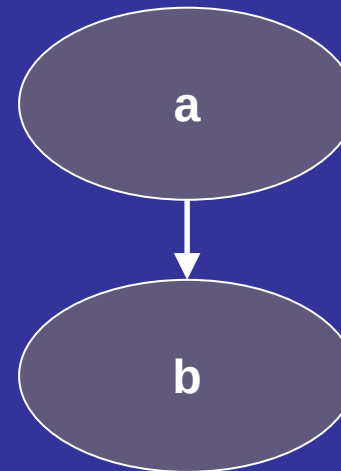
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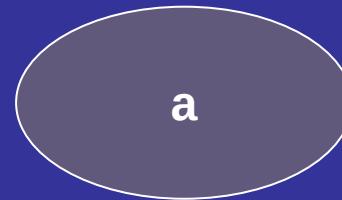
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        ...  
        b.wait()  
        ...  
    }  
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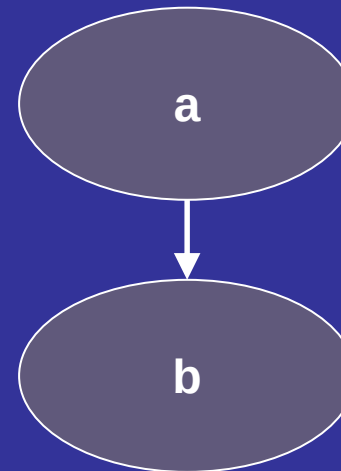
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synchronized (a) {  
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        ...  
        b.wait()  
        ...  
    }  
}
```



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```
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    synchronized (b) {  
        ...  
        b.wait()  
        ...  
    }  
}
```



Handling wait() and notify()

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```
synchronized (a) {  
    synchronized (b) {  
        ...  
        a.wait()  
        ...  
    }  
}
```

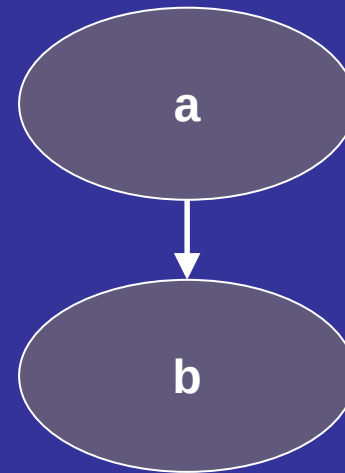


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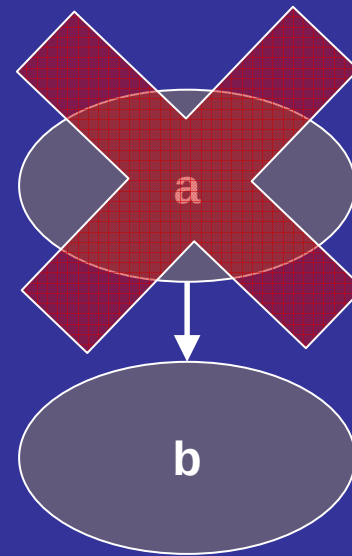
```
synchronized (a) {  
    synchronized (b) {  
        ...  
        a.wait()  
        ...  
    }  
}
```



Handling wait() and notify()

- Calling wait() releases and later reacquires receiver's lock
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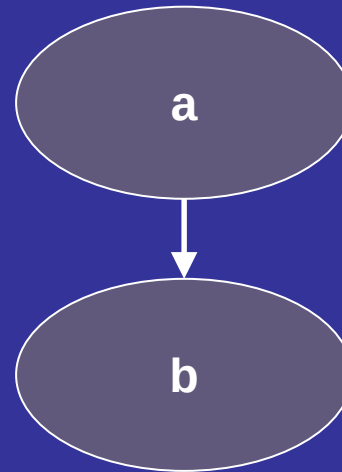
→ synchronized (a) {
 synchronized (b) {
 ...
 a.wait()
 ...
 }
}



Handling wait() and notify()

- Calling wait() releases and later reacquires receiver's lock
 - Considered no-op if receiver's lock most recently acquired
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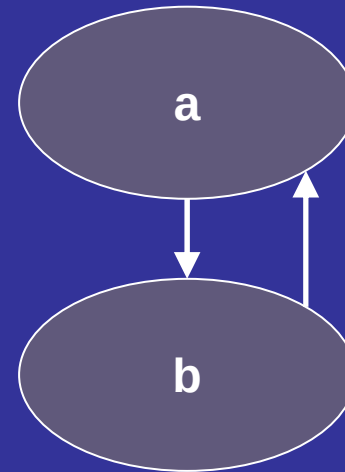
```
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        ...  
        a.wait()  
        ...  
    }  
}
```



Handling wait() and notify()

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```
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        ...  
        a.wait()  
        ...  
    }  
}
```

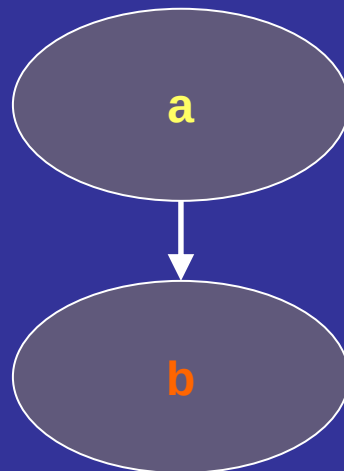
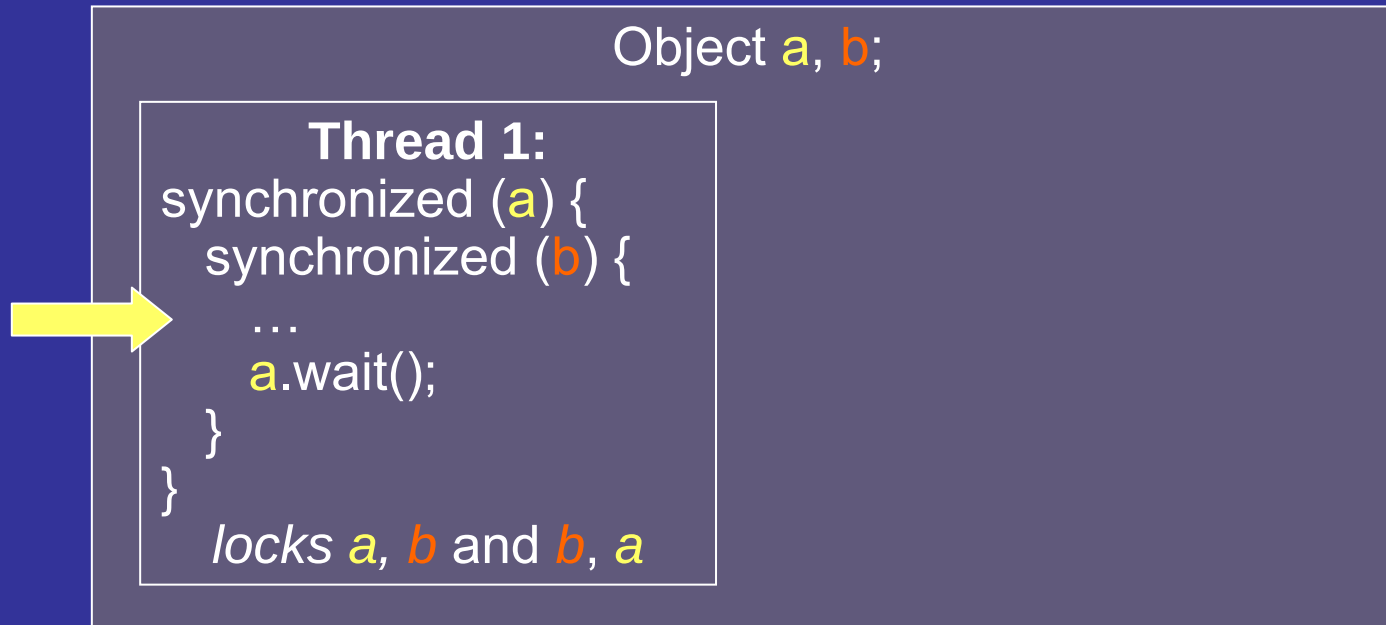


Deadlock using wait()

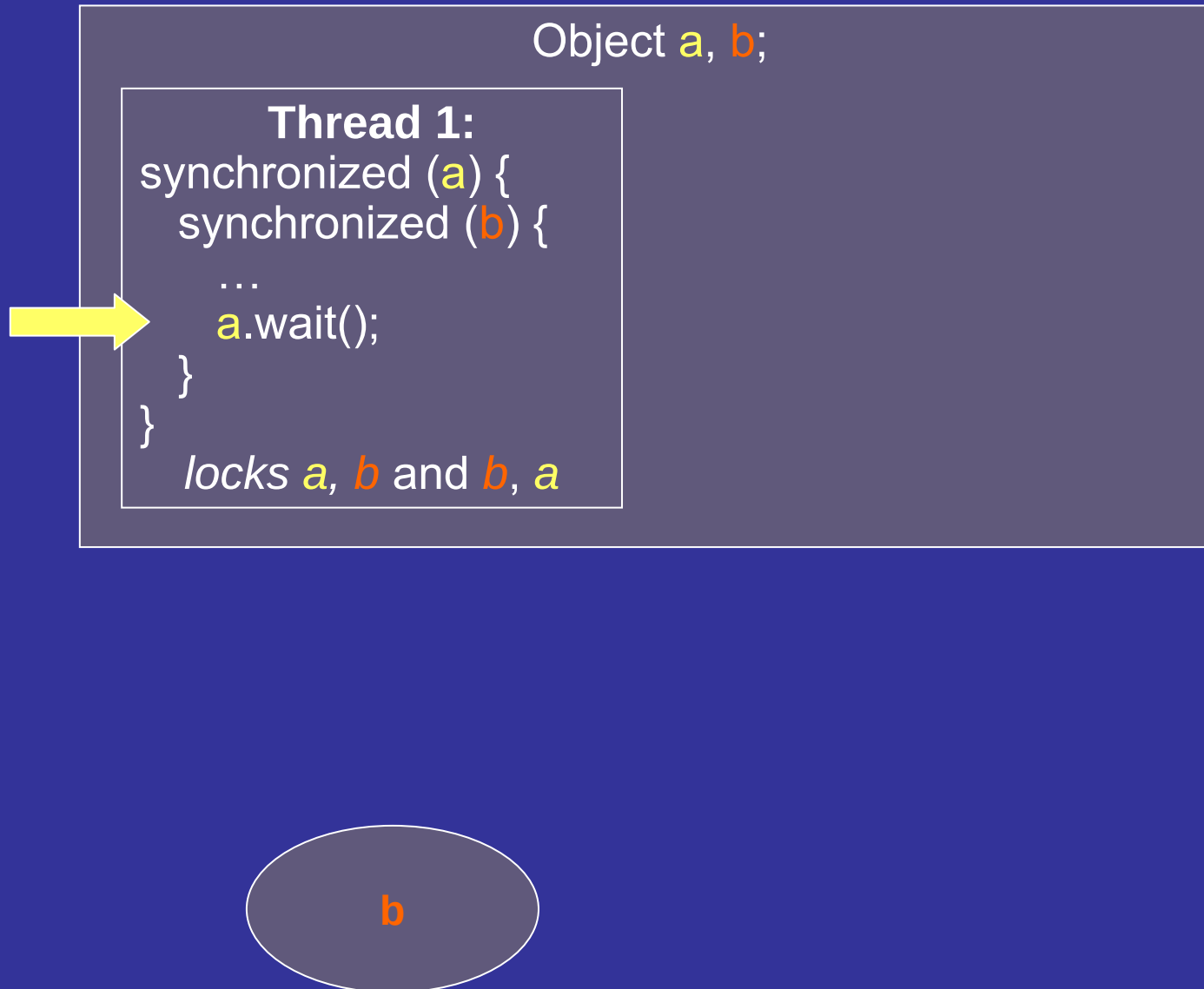
Object **a**, **b**;

```
Thread 1:  
synchronized (a) {  
    synchronized (b) {  
        ...  
        a.wait();  
    }  
}  
locks a, b and b, a
```

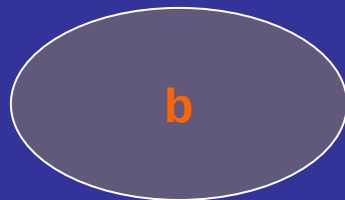
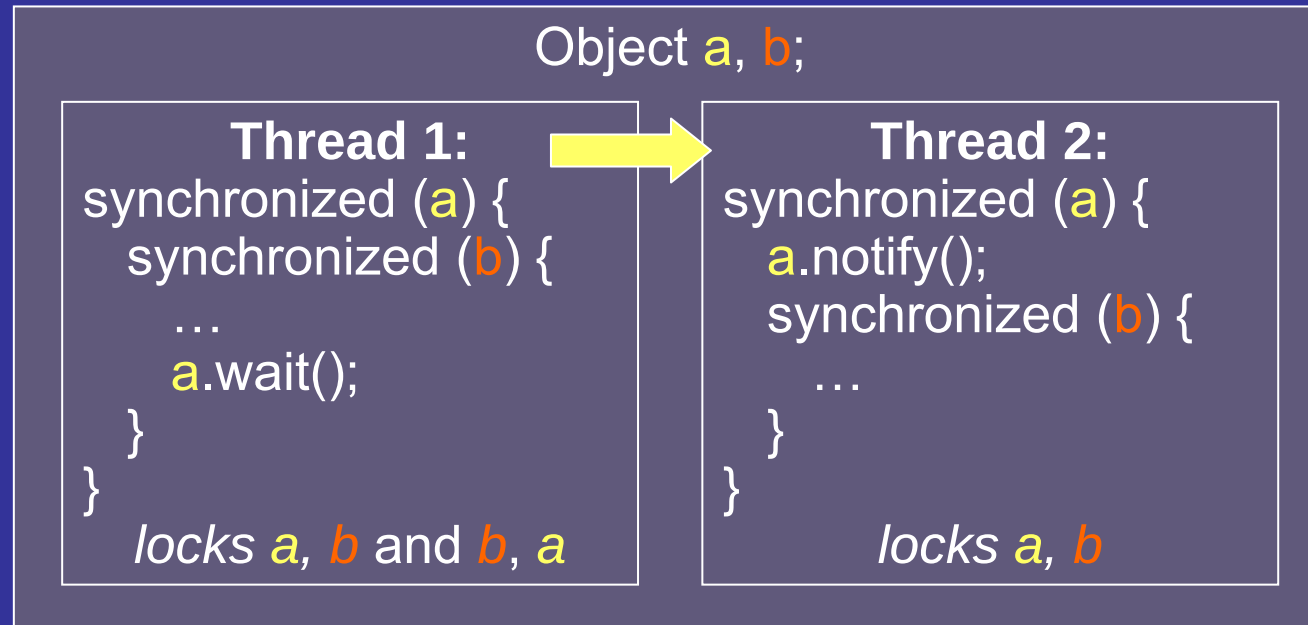
Deadlock using wait()



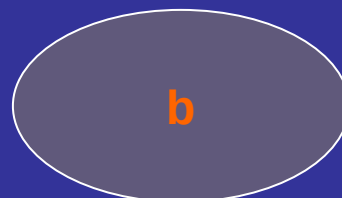
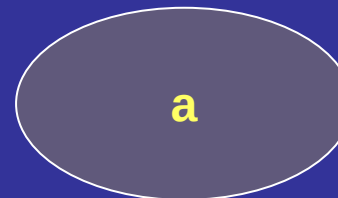
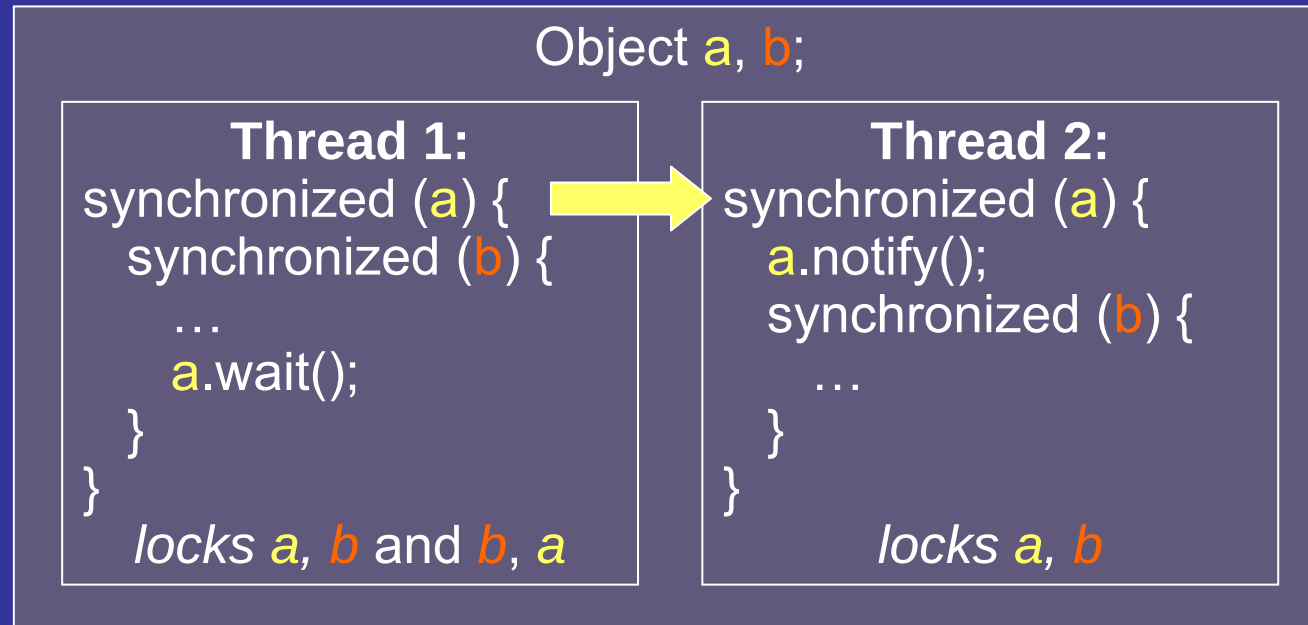
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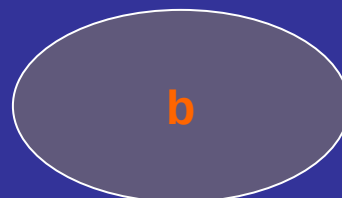
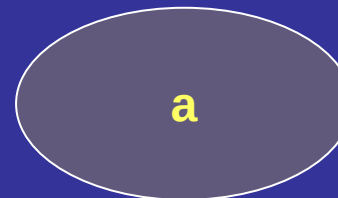
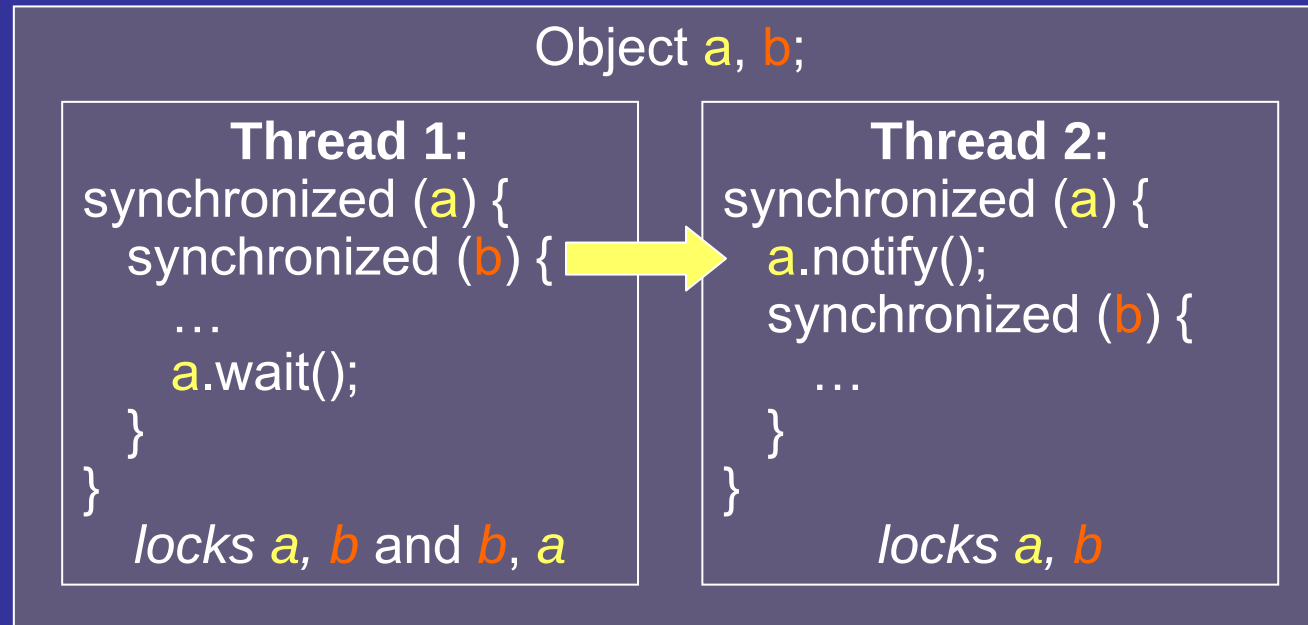
Deadlock using wait()



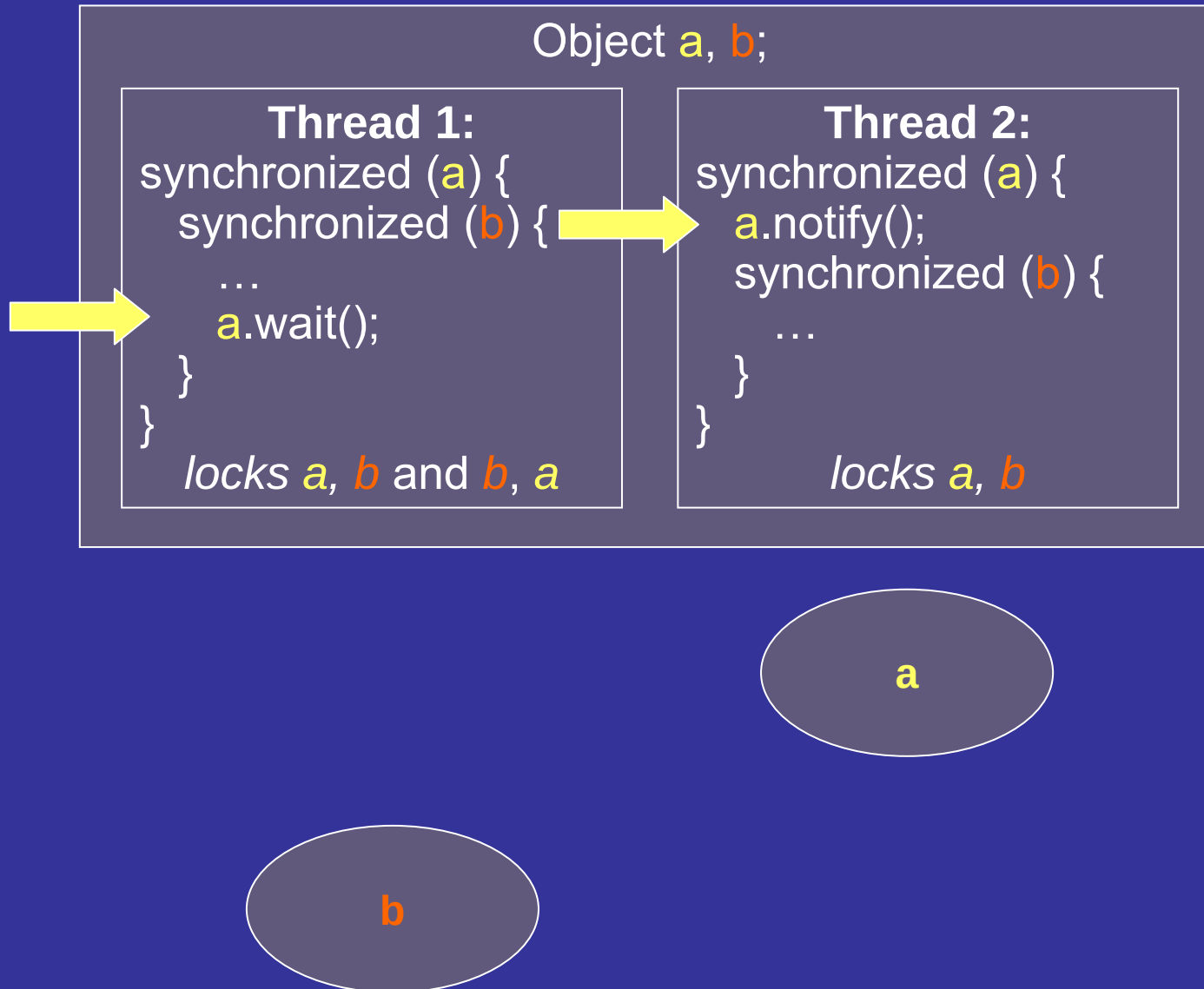
Deadlock using wait()



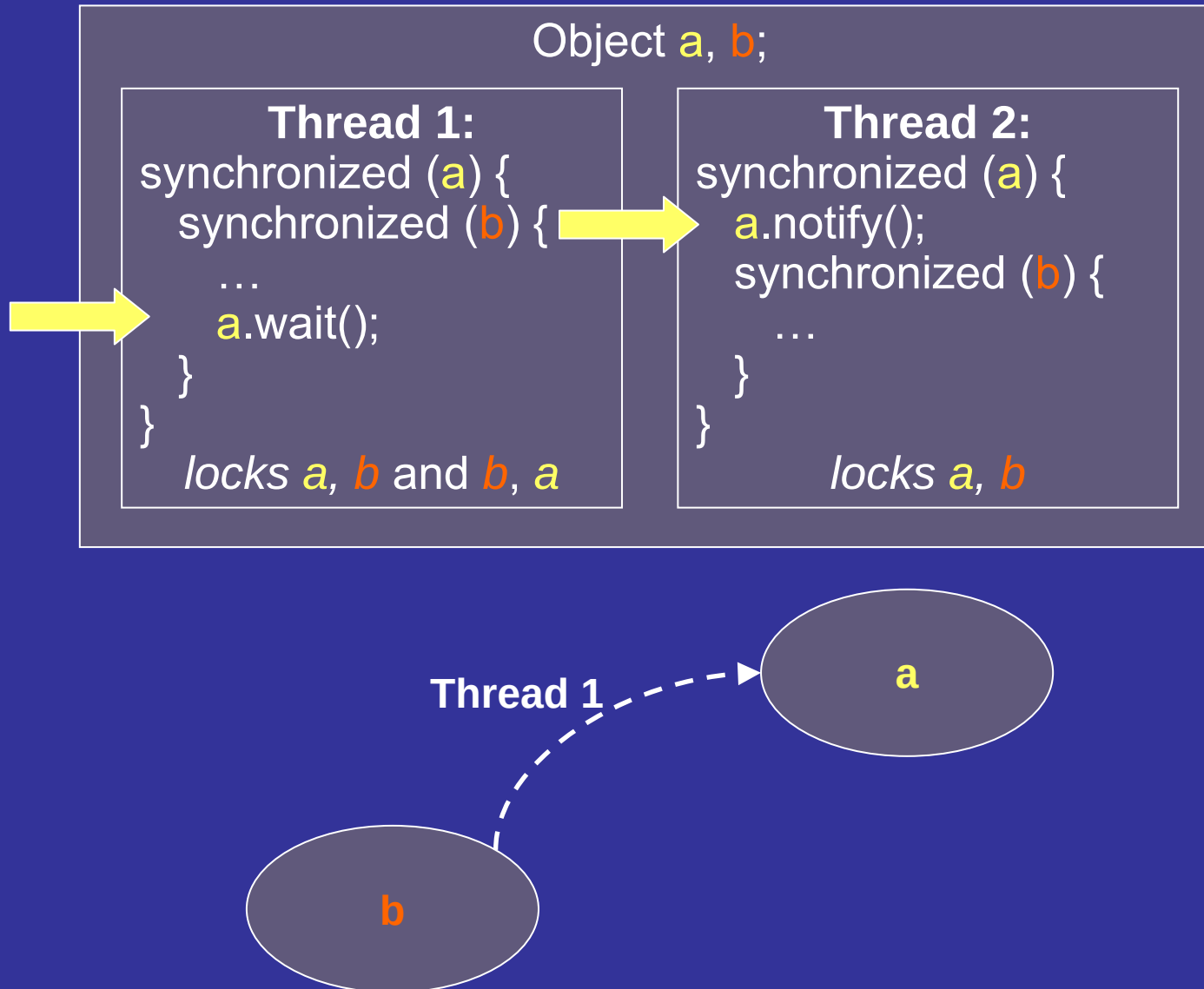
Deadlock using wait()



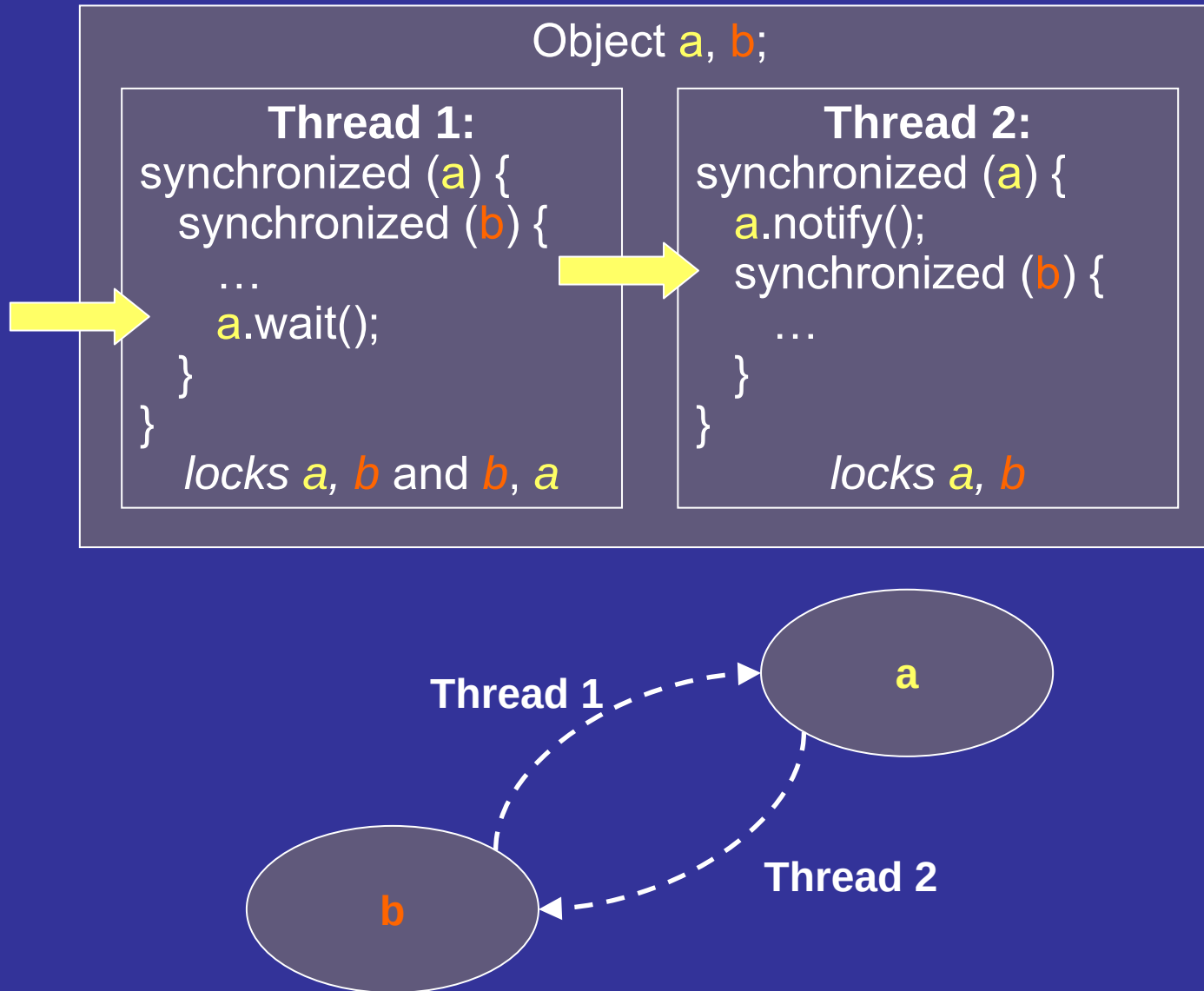
Deadlock using wait()



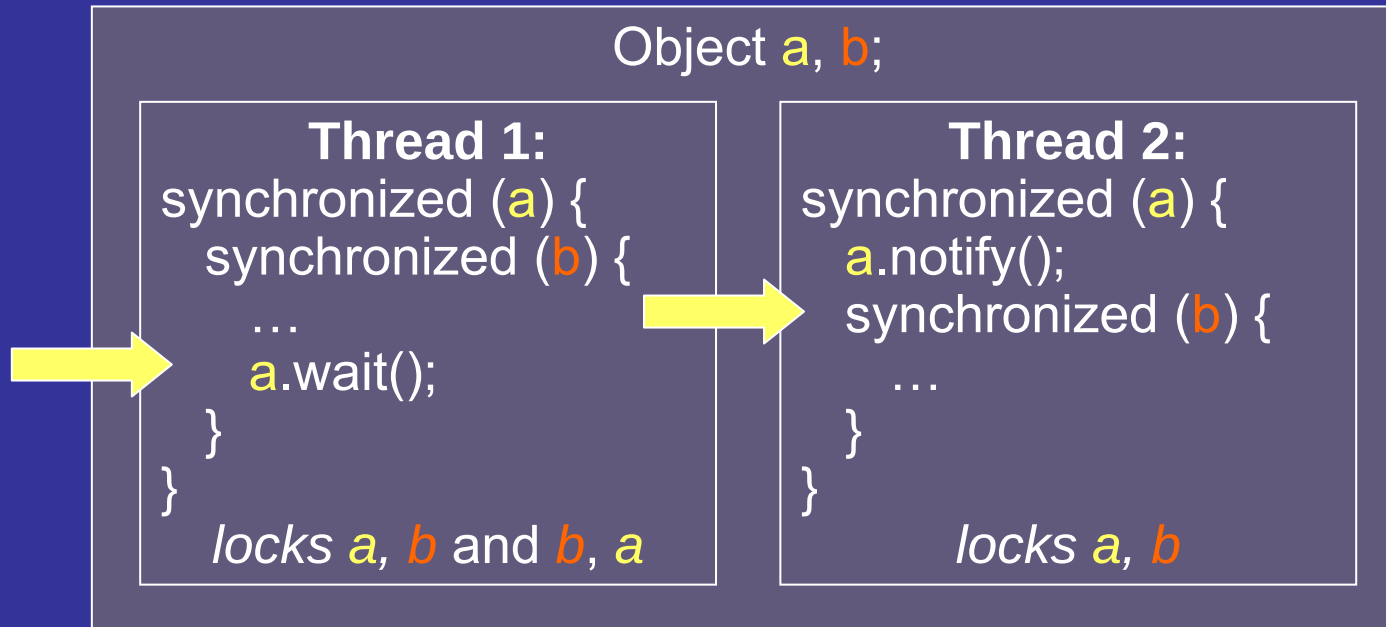
Deadlock using wait()



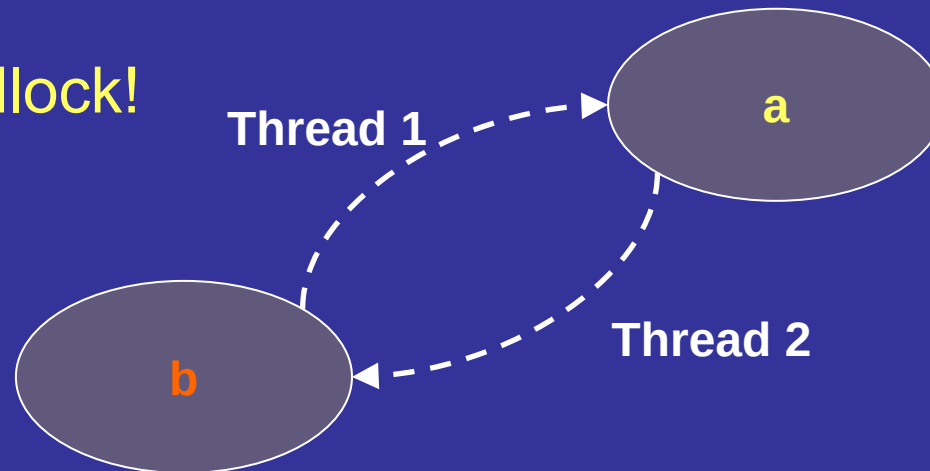
Deadlock using wait()



Deadlock using wait()



Deadlock!



Improving Precision

- We further refine may-alias sets and type information in certain cases (see paper)
 - Unaliased fields
 - Caller / callee type resolution
 - Final and effectively-final fields
- These optimizations prove very effective: one library went from 909 reports to only 1
- Context-sensitivity (integrating callee graphs) greatly improved precision

Outline

- Introduction
- Deadlock Detection Algorithm
- **Results**
- Related Work and Conclusions

Deadlocks Detected

- Analysis is sound: detects all deadlocks in library under analysis
- Assumptions:
 - Clients assumed to respect lock order of library for any shared locks
 - Callbacks are not modeled
 - The client code may call any public method
 - Would introduce many locking orders which are unlikely in practice
 - Reflection not handled

Deadlock Reports

- Each report: set of variables possibly involved in deadlock
- Also provided: set of methods possibly deadlocking using those variables
 - Sometimes many call sequences per report

Results: Overview

- Analyzed 18 libraries
- 13 libraries verified to be deadlock-free
 - Each library analyzed in under 3 minutes
- 5 libraries not verified
 - Exhibited 14 distinct deadlocks
 - Each library analyzed in under 3 minutes employing filtering heuristics

Deadlock-Free Libraries

Library	sync	kLOC	Reports
jcurzez	24	4	1
httpunit	17	23	0
jasperreports	11	67	0
croftsoft	11	14	2
dom4j	6	41	1
cewolf	6	7	0
jfreechart	5	125	0
htmlparser	5	22	0
jpcap	4	8	0
treemap	4	7	0
PDFBox	2	28	0
UJAC	1	63	0
JOscarLib	1	6	0

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htmlp			
jpcap			
treemap	4	7	0
PDFBox	2	28	0
UJAC	1	63	0
JOscarLib	1	6	0

Manually verified 4 reports to be false positives

Non-verified Libraries

Library	<code>sync</code>	kLOC	Reports	Deadlocks Found
JDK	1458	419	Out of Memory	7
Classpath	754	295	Out of Memory	5
ProActive	199	63	≥ 196	2
Jess	111	27	≥ 269	0
sdsu	69	26	$\geq 20,479$	0

Deadlocked JVM for all 14 cases

Filtering Heuristics

- Full analysis can yield too many reports
- Cycle length
 - Do not report cycles longer than 2 nodes
- Assume runtime type same as declared type
 - Lock declared as Object cannot alias with subclasses
- May filter out real deadlocks

Non-verified Libraries

Library	sync	kLOC	Reports	Reports (Filtered)	Deadlocks Found
JDK	1458	419	Out of Memory	72	7
Classpath	754	295	Out of Memory	32	5
ProActive	199	63	≥ 196	3	2
Jess	111	27	≥ 269	23	0
sdsu	69	26	$\geq 20,479$	3	0

Deadlocked JVM for all 14 cases

Non-verified Libraries

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sdsu	69	26	$\geq 20,479$	3	0

Deadlocked JVM for all 14 cases

Deadlocks Found

	JDK	Classpath
BeanContextSupport	×	Not Implemented
StringBuffer	×	×
synchronized Collections	×	×
PrintWriter/CharArrayWriter	×	
java.awt.dnd.DropTarget	×	Not synchronized
java.awt.EventQueue	×	×
java.awt.Menu	×	Not Implemented
java.util.SimpleTimeZone	Not synchronized	×
java.util.logging.Logger		×

ProActive: ProxyForGroup, AbstractDataObject

PrintWriter/CharArrayWriter: JDK

```
class Writer {  
    Object lock;  
    protected Writer() {  
        lock = this;  
    }  
  
    protected Writer(Object lock) {  
        this.lock = lock;  
    }  
}
```

```
class PrintWriter extends Writer {  
    Writer out;  
    public PrintWriter(Writer out) {  
        super(out); this.out = out;  
    }  
    public void write(...) {  
        synchronized (lock) {  
            out.write(...)  
        }  
    }  
}
```

```
CharArrayWriter c = new CharArrayWriter();  
PrintWriter p1 = new PrintWriter(c);  
PrintWriter p2 = new PrintWriter(p1);
```

Thread 1:
p2.write(...);
locks p1, c

Thread 2:
c.writeTo(p2);
locks c, p1

PrintWriter/CharArrayWriter: JDK

```
class Writer {  
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        }  
    }  
}
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CharArrayWriter c = new CharArrayWriter();  
PrintWriter p1 = new PrintWriter(c);  
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```

Thread 1:
p2.write(...);
locks p1, c

Thread 2:
c.writeTo(p2);
locks c, p1

c.lock = c
p1.lock = c
p2.lock = p1

PrintWriter/CharArrayWriter: Classpath

```
class Writer {  
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    }  
  
    protected Writer(Object lock) {  
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    }  
}  
  
class PrintWriter extends Writer {  
    public PrintWriter(Writer out) {  
        super(out.lock);  
    }  
  
    public void write(...) {  
        synchronized (lock) { ... }  
    }  
}
```

```
CharArrayWriter c = new CharArrayWriter();  
PrintWriter p1 = new PrintWriter(c);  
PrintWriter p2 = new PrintWriter(p1);
```

No deadlock!

PrintWriter/CharArrayWriter: Classpath

```
class Writer {  
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    }  
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```

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PrintWriter p2 = new PrintWriter(p1);
```

No deadlock!

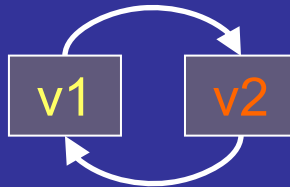
```
c.lock = c  
p1.lock = c  
p2.lock = c
```

ProActive's ProxyForGroup

- ProxyForGroup method asynchronousCallOnGroup() can be made to lock both **this** and any other ProxyForGroup object
 - Complicated state required to produce this scenario
 - Setup code spans 23 lines, with 11 objects created, and 6 methods invoked

Cyclic Deadlocks

- `java.util.Vector` can be deadlocked by forming a cycle with two `Vector` instances



Vector `v1`, `v2`; Object `o`;
`v1.add(v2)`;
`v2.add(v1)`;

Thread 1:
`v1.contains(o)`;
locks `v1`, `v2`

Thread 2:
`v2.contains(o)`;
locks `v2`, `v1`

- Similar deadlock in
 - All other synchronized Collections
 - Combinations of those Collections
- This deadlock only counted once for JDK and Classpath
 - 5 other deadlocks

Resolving Deadlocks

- Two possible solutions:
 - Rewrite methods to acquire locks in set order
 - Extend Java with synchronization primitive to atomically acquire multiple locks (can also write this as a library method)
- Issue: must know locks
 - Can sometimes write helper methods to determine locks
 - Locks may change while being determined
 - Global lock or transactions are alternatives

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Related Work

- Using lock-order graphs:
 - Jlint [Artho, Biere 2001]; von Praun 2004
 - For programs, do not detect all deadlocks
- RacerX [Engler, Ashcraft 2003]
 - Non-hierarchical locking (for C), requires annotations, does not detect all deadlocks
- Model Checking:
 - Demartini, Iosif, Sisto 1999
 - Java Pathfinder: Havelund, Pressburger 2000
 - For programs, not scalable
- Ownership Types:
 - Boyapati, Lee, Rinard 2002
 - Requires annotations, restricts programming model

Conclusions

- Our analysis is effective at
 - Verifying libraries to be free from deadlock
 - Finding deadlocks
- Analysis of libraries can be effective at finding library specific defects



Sources of Imprecision

- Consider infeasible aliasing / sharing across threads
 - Do not track flow of values through fields
- Consider infeasible paths of control