CS492B Analysis of Concurrent Programs

Deadlock Bug Detection Techniques

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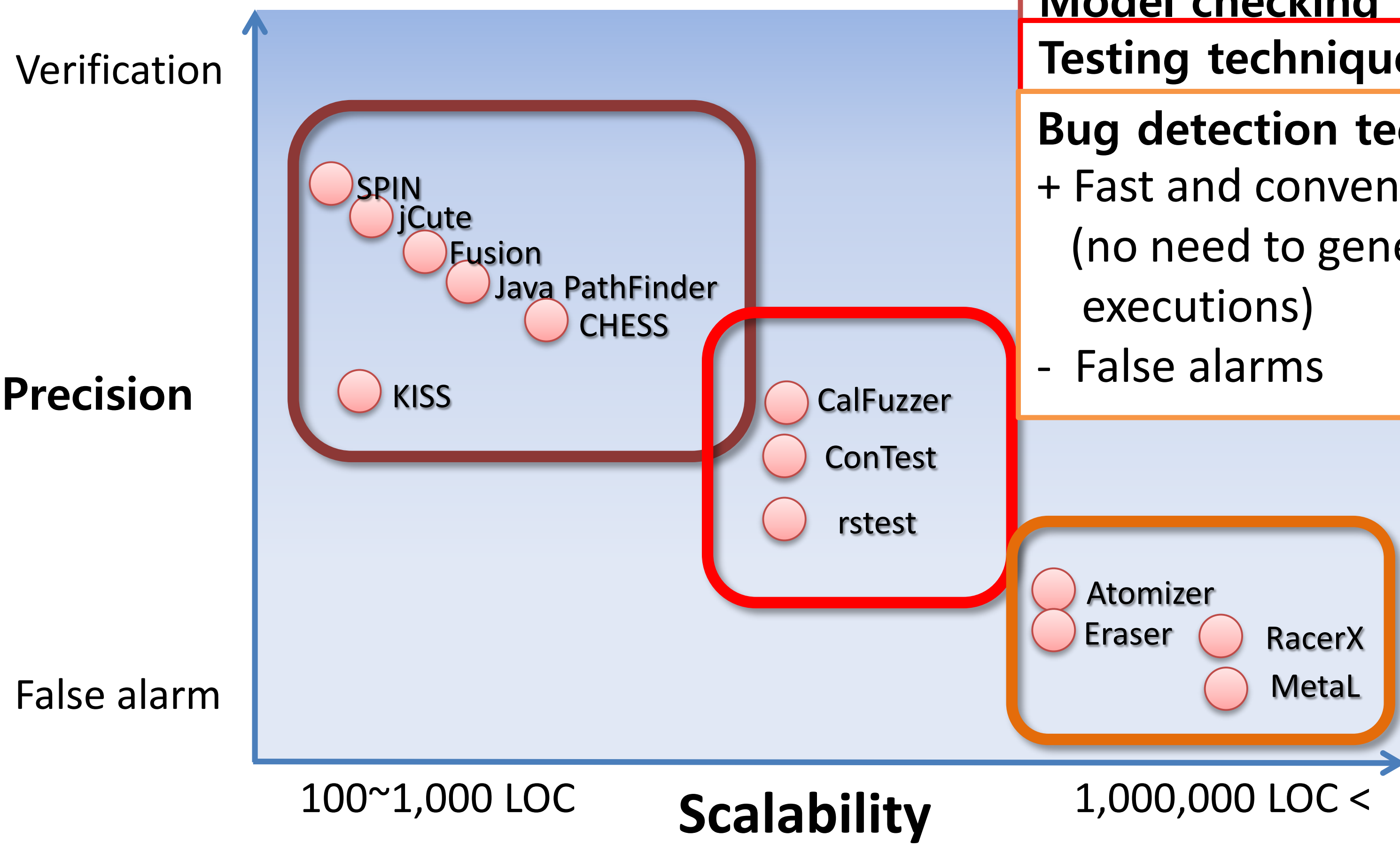
Bug Detection Techniques for Concurrent Programs



Model checking techniques

Testing techniques

Bug detection techniques

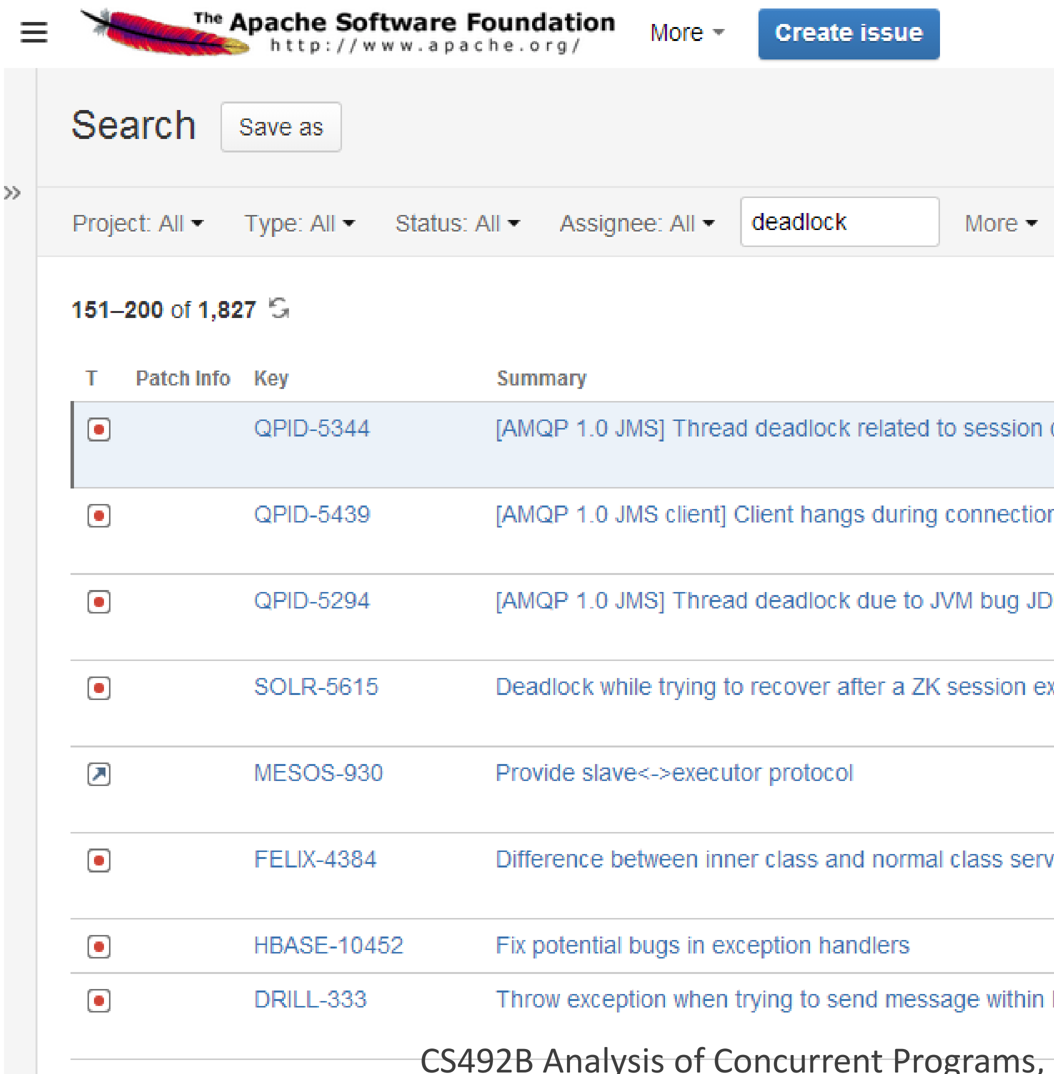
+ Fast and convenient
  (no need to generate many executions)
- False alarms

Deadlock Bugs Frequently Occur in Real World

Application	What it does	Non-Deadlock	Deadlock
MySQL	Database Server	14	9
Apache	Web Server	13	4
Mozilla	Web Browser	41	16
OpenOffice	Office Suite	6	2
Total		74	31

- In a survey on 105 real-world concurrency bugs in open-source applications, **31 out of 105 bugs are deadlock bugs** [Lu *et al*., ASPLOS 08]

Deadlock Bugs Frequently Occur in Real World



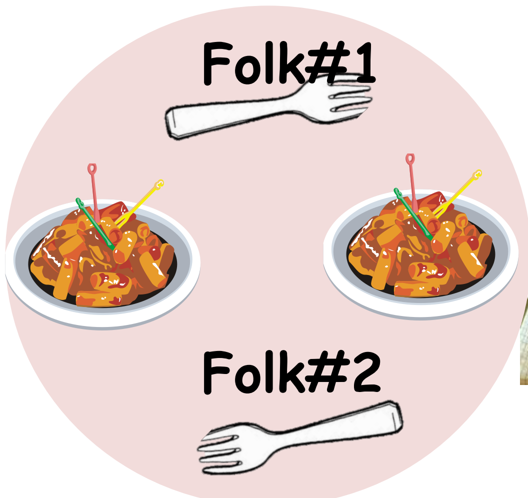
- According to Apache bug tracking systems, there have been **200 deadlock related issues since 2014**

Deadlock

- A deadlock occurs when each of a set of threads is blocked, waiting for another thread in the set to satisfy certain condition
  - **release shared resource**
  - **raise event**

Resource Deadlock

- Ex. Dining philosopher problem



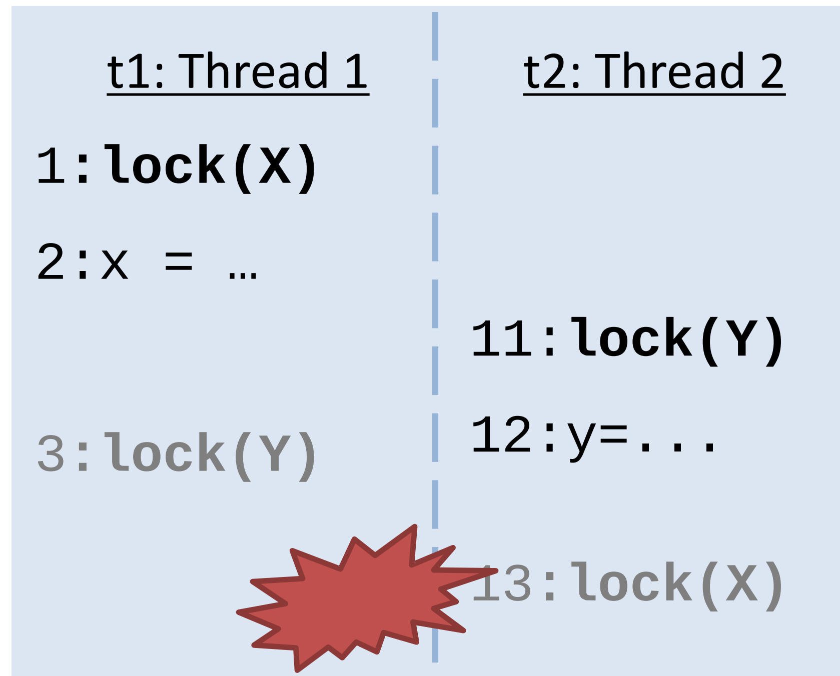
[Milner]	[Dijkstra]
Pick up **Folk#1**	
	Pick up **Folk#2**
Wait for **Folk#2**	
	Wait for **Folk#1**

Resource Deadlock in Concurrent Programs

- ABBA deadlock

```
 Thread1() {
1: lock(X)
2: x = … ;
3: lock(Y)
4: y = … ;
5: unlock(Y)
6: unlock(X)
 }
```

```
 Thread2() {
11: lock(Y)
12: y = … ;
13: lock(X)
14: x = … ;
15: unlock(X)
16: unlock(Y)
 }
```



Non-blocking Algorithm

- An algorithm is called non-blocking if failure or suspension of any thread cannot cause failure or suspension of another thread
  - a non-blocking algorithm is lock-free if there is guaranteed system-wide progress, and wait-free if there is also guaranteed per-thread progress.
- Blocking a thread is undesirable for many reasons while non-blocking algorithms do not suffer from these downsides
  - while the thread is blocked, it cannot accomplish anything
  - certain interactions between locks can lead to error conditions such as deadlock, livelock, and priority inversion.
  - using locks involves a trade-off between coarse-grained locking, which can significantly reduce opportunities for parallelism, and fine-grained locking, which requires more careful design, increases locking overhead and is more prone to bugs.

Communication Deadlock

- Lost notify

```
  Thread1() {
1: ...
2: for(i=0;i<10;i++){
3:  wait(m) ;}
  }
```

```
   Thread2() {
11: ...
12: for(j=0;j<10;j++){
13:  notify(m);}
   }
```

t_1: Thread 1	t_2: Thread 2
`3:wait(m)//i==0`	
…	
	`13:notify(m)//j==0`
	…
	`13:notify(m)//j==9` (terminate)
`3:wait(m)//i==9`	

public final void wait()

- Causes the current thread to wait until another thread invokes the notify() method or the notifyAll() method for this object.
- The current thread must own this object's monitor.
  - The thread releases ownership of this monitor and waits until another thread notifies threads waiting on this object's monitor to wake up either through a call to the notify method or the notifyAll method. The thread then waits until it can re-obtain ownership of the monitor and resumes execution.
- Interrupts and spurious wakeups are possible, and this method should always be used in a loop:

```
synchronized (obj) {
  while (<condition does not hold>)
    obj.wait();
  ... // Perform action appropriate to condition
}
```

See the following stackoverflow discussion: http://stackoverflow.com/questions/1050592/do-spurious-wakeups-actually-happen

`public final void notify()`

- Wakes up a single thread that is waiting on this object's monitor.
  - If any threads are waiting on this object, one of them is chosen to be awakened. The choice is arbitrary and occurs at the discretion of the implementation.
- The awakened thread will not be able to proceed until the current thread relinquishes the lock on this object.
  - The awakened thread will compete in the usual manner with any other threads that might be actively competing to synchronize on this object; for example, the awakened thread enjoys no reliable privilege or disadvantage in being the next thread to lock this object.
- This method should only be called by a thread that is the owner of this object's monitor. A thread becomes the owner of the object's monitor in one of three ways:
  - By executing a synchronized instance method of that object.
  - By executing the body of a synchronized statement that synchronizes on the object.
  - For objects of type Class, by executing a synchronized static method of that class.

Finding Deadlock Bugs is Difficult

- A deadlock bug induces deadlock situations **only under certain thread schedules**
- Systems software creates a **massive number of locks** for fine-grained concurrency controls
- **Function caller-callee relation** complicates the reasoning about possible nested lockings

Bug Detection Approach

Resource deadlock

- Basic potential deadlock detection algorithm
- GoodLock algorithm

Communication deadlock

- CHECKMATE: a trace program model-checking technique for deadlock detection

Basic Potential Deadlock Detection

- Extend the cyclic deadlock monitoring algorithm
- Cyclic deadlock monitoring algorithm (e.g. *LockDep*)
  - Monitor lock acquires and releases in runtime
  - Lock graph (N, E_N)
    - Create a node n_X when a thread acquires lock X
    - Create an edge (n_X, n_Y) when a thread acquires lock Y while holding lock X
    - Remove n_X , $(n_X, *)$ and $(*, n_X)$ when a thread releases X

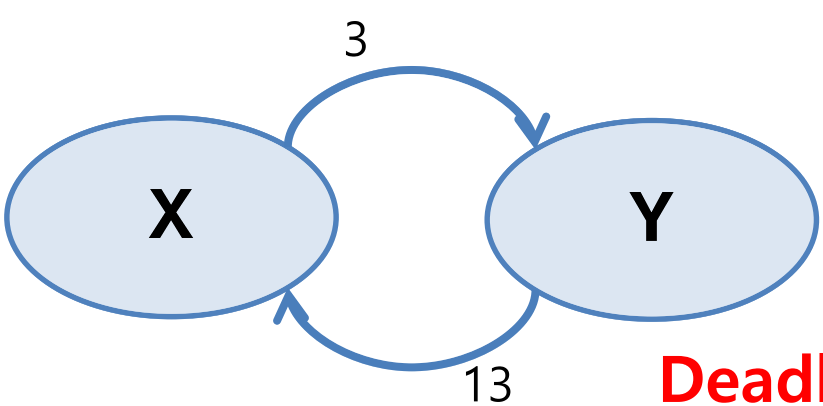
  → Report deadlock when the graph has any cycle

Cyclic Deadlock Detection Example (1/2)

```
  Thread1() {
1:  lock(X)
2:  a = … ;
3:  lock(Y)
4:  b = … ;
5:  unlock(Y)
6:  unlock(X)
  }
```

```
  Thread2() {
11:  lock(Y)
12:  b = … ;
13:  lock(X)
14:  a = … ;
15:  unlock(X)
16:  unlock(Y)
  }
```

t1: Thread 1	t2: Thread 2
1:lock(X)	
2:a = …	
	11:lock(Y)
3:lock(Y)	12:b=...
	13:lock(X)



Deadlock detected!

Cyclic Deadlock Detection Example (2/2)

```
  Thread1() {            Thread2() {
1: lock(X);           11: lock(Y);
2: a = …              12: b = …
3: lock(Y);           13: lock(X);
4: b = …              14: a = …
5: unlock(Y);         15: unlock(X);
6: unlock(X);         16: unlock(Y);
  }                      }
```

t1: Thread 1	t2: Thread 2
1:**lock(X)**	
2:a = …	
3:**lock(Y)**	
4:b = …	
5:**unlock(Y)**	
	11:**lock(Y)**
6:**unlock(X)**	
	12:b =...
	13:**lock(X)**
	14:a =...
	15:**unlock(X)**
	16:**unlock(Y)**

No problem

Basic Deadlock Prediction Technique

- Potential cyclic deadlock detection algorithm [Harrow, SPIN 00]
  - Lock graph (N, E_N)
    - Create a node n_X when a thread acquires lock X
    - Create an edge (n_X, n_Y) when a thread acquires lock Y while holding lock X
    - ~~Remove n_X, $(n_X, *)$ and $(*, n_X)$ when a thread releases X~~

    → Report potential deadlocks if the resulted graph at the end of an execution has a cycle

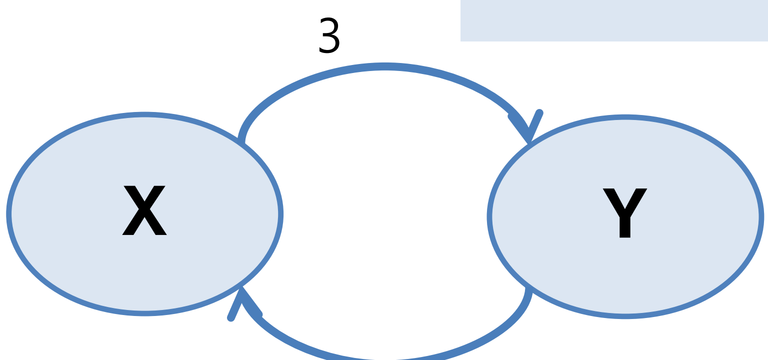
[Harrow, SPIN 00] J. J. Harrow, Jr.: Runtime checking of multithreaded applications with Visual Threads, SPIN Workshop 2000

Potential Cyclic Deadlock Detection Example

```
  Thread1() {
1:  lock(X)
2:  a = … ;
3:  lock(Y)
4:  b = … ;
5:  unlock(Y)
6:  unlock(X)
  }
```

```
  Thread2() {
11:  lock(Y)
12:  b = … ;
13:  lock(X)
14:  a = … ;
15:  unlock(X)
16:  unlock(Y)
  }
```

t1:Thread 1	t2:Thread 2
1:lock(X)	
2:a = …	
3:lock(Y)	
4:b = …	
5:unlock(Y)	
	11:lock(Y)
6:unlock(X)	
	12:b=...
	13:lock(X)
	...



Cycle → Potential deadlock

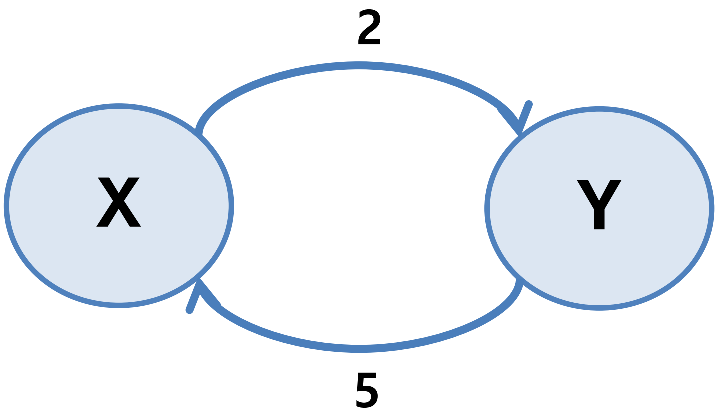
Basic Deadlock Prediction Technique

- The algorithm is commercialized as a SW tool VisualThreads (*HP*)
- Empirical results show that the algorithm is very effective to discover hidden deadlock bugs
- Challenge: generate many false positive

False Positive Example#1 – Single Thread Cycle

```
  Thread1() {
1: lock(X);
2:  lock(Y);
3:  unlock(Y);
4: unlock(X);

5: lock(Y);
6:  lock(X);
7:  unlock(X);
8: unlock(Y);}
```

```
   Thread2() {
11: lock(X);
12: unlock(X);

13: lock(Y);
14: unlock(Y);}
```



The lock graph has a cycle, but no deadlock

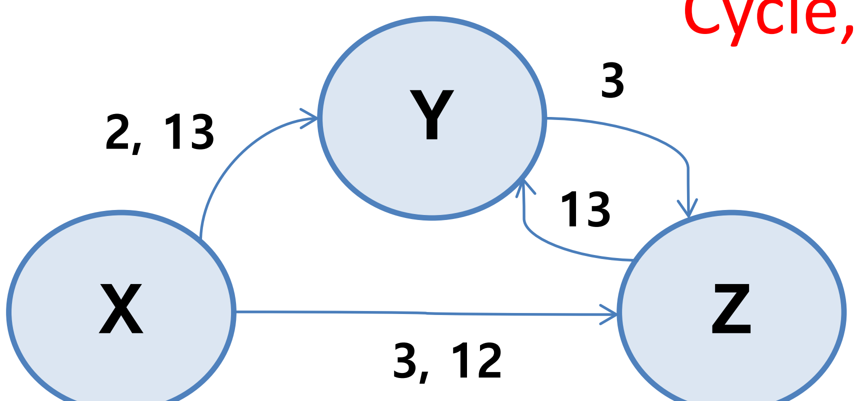
A cycle that consists of edges created by one thread is a false positive

False Positive Example#2: Gate Lock

```
   Thread1() {                Thread2() {
1:  lock(X);               11:  lock(X);
2:   lock(Y);              12:   lock(Z) ;
3:    lock(Z) ;            13:    lock(Y) ;
4:    unlock(Z);           14:    unlock(Y);
5:   unlock(Y);            15:   unlock(Z);
6: unlock(X); }            16: unlock(X);
```

Gate lock (guard lock)

Cycle, but no deadlock



False Positive Example#3: Thread Creation

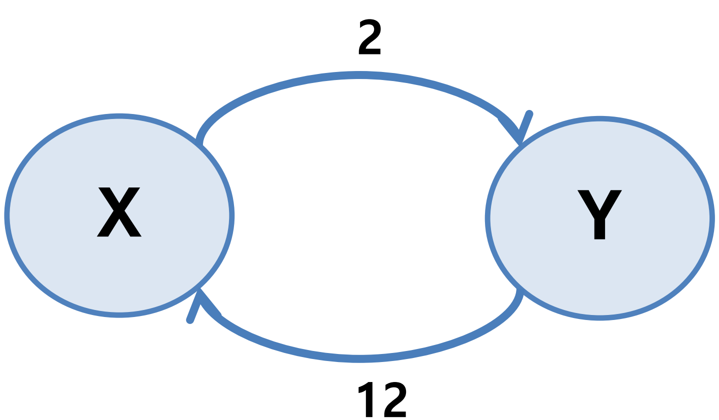
```
main(){
0:  start(f1);
}
```

Thread segment#1

```
f1(){
1: lock(X);
2:  lock(Y);
3:  unlock(Y);
4: unlock(X);
5: start(f2);
}
```

Thread segment#2

```
f2(){
11: lock(Y) ;
12:  lock(X);
13:  unlock(X);
14: unlock(Y);
}
```



Cycle, but no deadlock

GoodLock Algorithm[Agarwal, IBM 10]

- Extend the lock graph in the basic potential deadlock detection algorithm to consider *thread, gate lock,* *and* *thread segment*
- Thread segment graph (S, E_S)
  - When the main thread t_0 starts:
    - Create a thread segment node s_0 ;
    - map t_0 to s_0 ($M(t_0) = s_0$);
    - $n = 1$.
  - When a thread t_i starts a new thread t_j
    - Create two thread segment nodes s_n and s_{n+1} ;
    - Create two edges ($M(t_i)$, s_n) *and* ($M(t_i)$, s_{n+1}) ;
    - $M(t_i) = s_n$; $M(t_j) = s_{n+1}$;
    - $n = n + 2$;

[Agarwal, IBM 10] R. Agarwal et al., Detection of deadlock potential in multithreaded programs, IBM Journal of Research and Development, 54(5), 2010

Thread Segment Graph Example

t0 : main()

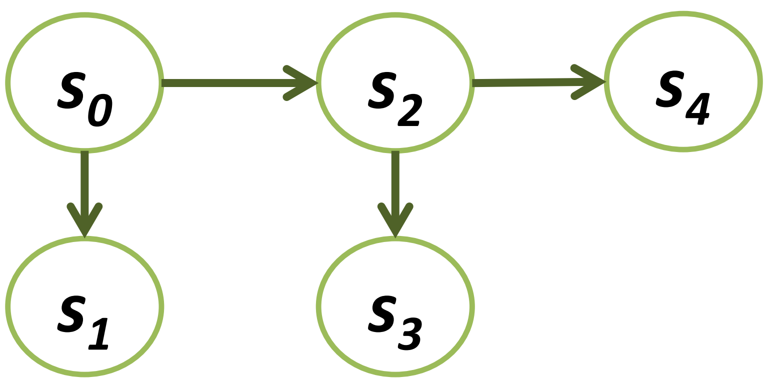
```
main(){
0: …                         s0
1: start(f1);
2: …                         s1
}
```

t1: f1()

```
  f1(){                      s2
1: lock(X);
2: lock(Y);
3: start(f2);
4: unlock(Y);                s3
5: unlock(X);}
```

t2: f2()

```
  f2(){                      s4
11: lock(Y) ;
12: lock(X);
13: unlock(X);
14: unlock(Y);
```



Extended Lock Graph

- Lock graph (N, E_N)
  - Create a node n_X when a thread acquires lock X
  - Create an edge (n_X, L, n_Y) when a thread acquires lock Y while holding lock X, where $L = (s_1, t, G, s_2)$
    - s_1: the thread segment ($s_1 \in S$) where lock X was acquired
    - t: the thread that acquires lock Y
    - G: the set of locks that t holds when it acquires Y
    - s_2: the thread segment where lock Y was acquired

Potential Deadlock Detection

- A cycle is *valid* (i.e., true positive) when every pair of edges (m_{11}, (s_{11}, t_1, G_1, s_{12}), m_{12}), and (m_{21}, (s_{21}, t_2, G_2, s_{22}), m_{22}) in the cycle satisfies:
  - $t_1 \neq t_2$, and
  - $G_1 \cap G_2 = \emptyset$, and
  - $\neg(s_{12} \prec s_{21})$
    - The happens-before relation $\prec$ is the transitive closure of the relation R such that $(s_1, s_2) \in R$ if there exists the edge from s_1 to s_2 in the thread segment graph

Thread Creation Example Revisit

t0 : main()

```
main(){
0:  …                    s0
1:  start(f1);
2:  …                    s1
}
```

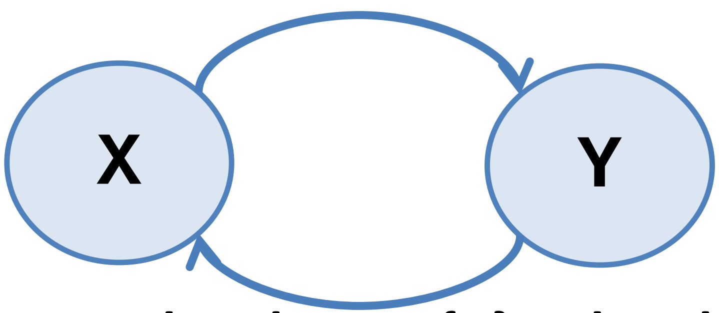
t1: f1()

```
  f1(){                  s2
1:  lock(X);
2:  lock(Y);
3:  start(f2);
4:  unlock(Y);           s3
5:  unlock(X);}
```

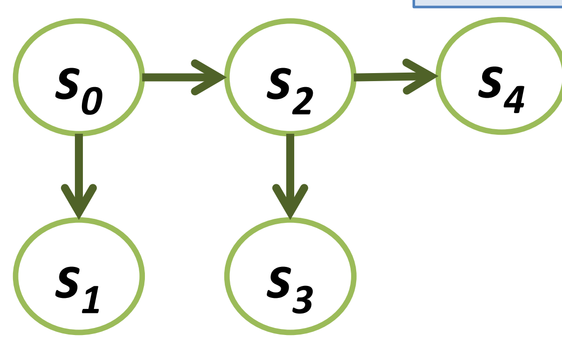
t2: f2()

```
  f2(){                  s4
11:  lock(Y) ;
12:  lock(X);
13:  unlock(X);
14:  unlock(Y);
```

e_1: (n_X, (s_2, t_1, {X}, s_2), n_Y)



e_2: (n_Y, (s_4, t_2, {Y}, s_4), n_X)



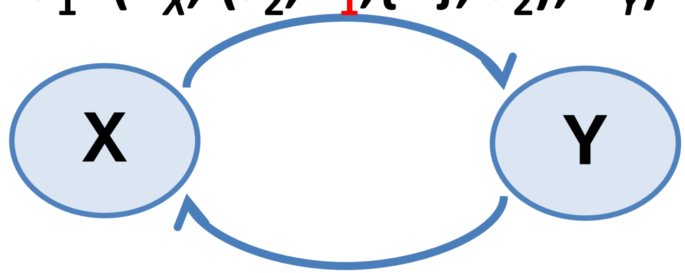
Revising Singe Thread Cycle Example

```
main() {
1: start(Thread1);
2: start(Thread2);
}
```

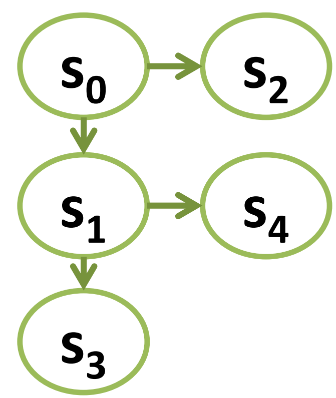
```
Thread1() {
11: lock(X);
12:  lock(Y);
13:  unlock(Y);
14: unlock(X);

15: lock(Y);
16:  lock(X);
17:  unlock(X);
18: unlock(Y);}
```

```
Thread2() {
21: lock(X);
22: unlock(X);

23: lock(Y);
24: unlock(Y);}
```

e_1: $(n_X, (s_2, t_1, \{X\}, s_2), n_Y)$



e_2: $(n_Y, (s_2, t_1, \{Y\}, s_2), n_X)$

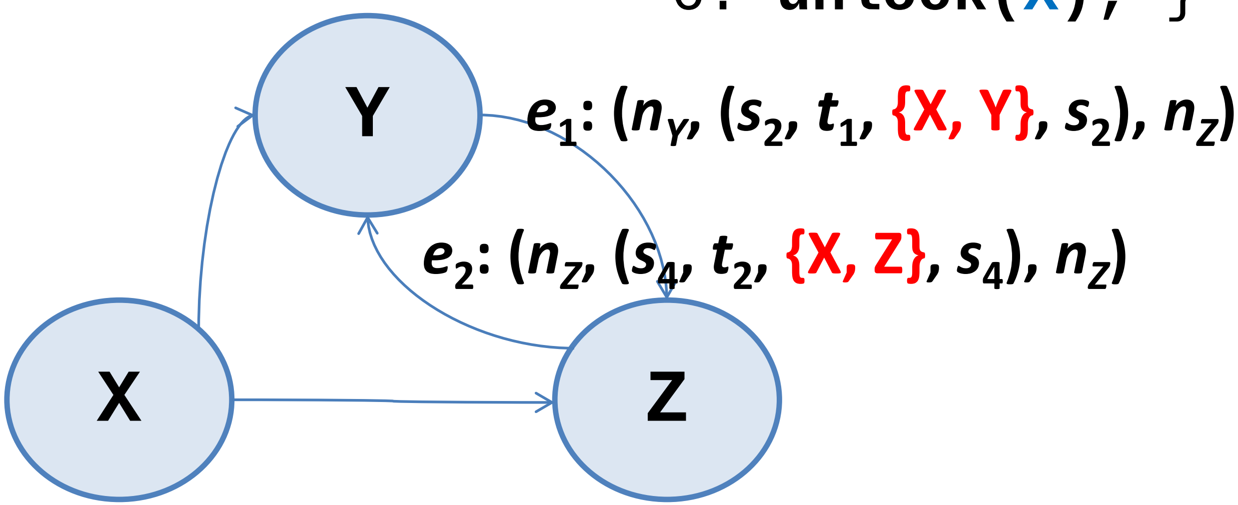


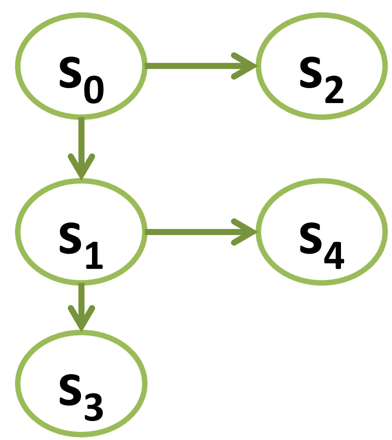
Revising Gate Lock Example

```
main() {
  start(Thread1);
  start(Thread2);
}
```

```
Thread1() {
1: lock(X);
2:   lock(Y);
3:     lock(Z) ;
4:     unlock(Z);
5:   unlock(Y);
6: unlock(X); }
```

```
Thread2() {
11: lock(X);
12:   lock(Z) ;
13:     lock(Y) ;
14:     unlock(Y);
15:   unlock(Z);
16: unlock(X);
```





Detecting Potential Deadlock with Wait/Notify, Semaphore, etc*

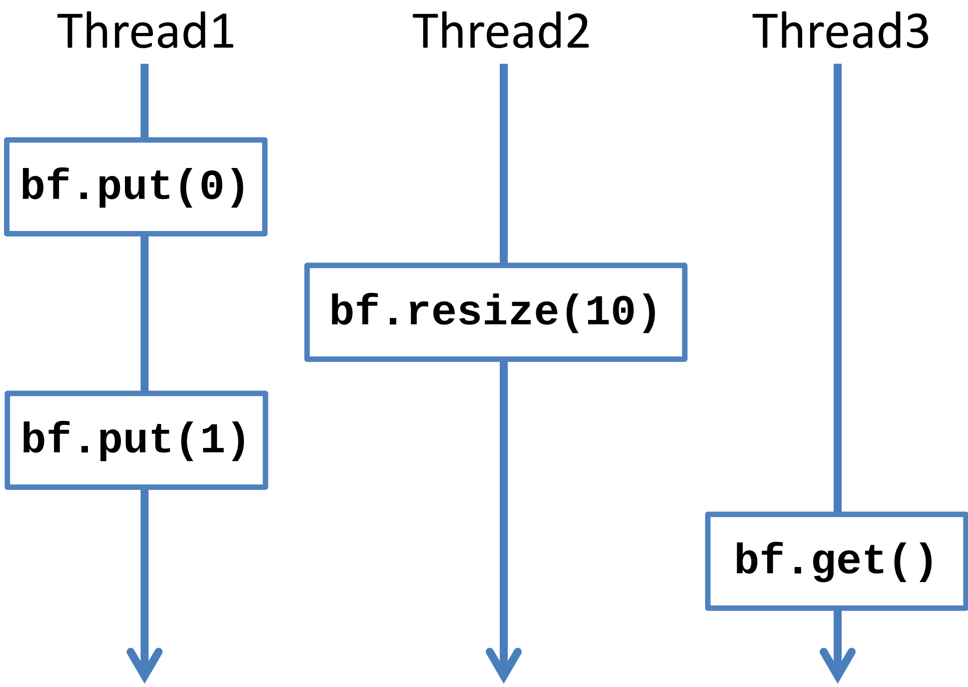
```
class BlockedBuffer {
 List buf = new ArrayList();
 int cursize = 0;
 int maxsize;

 BlockedBuffer(int max){
   maxsize = max;
 }

 sync boolean isFull(){
   return(cursize>=maxsize);
 }

 sync boolean isEmpty(){
   return(cursize == 0) ;
 }

 sync void resize(int m){
   maxsize = m;
 }
```

```
sync void put(Object e){
  while(isFull())
    wait() ;
  buf.add(e);
  cursize++ ;
  notify(); }


Object get(){
  Object e;
  sync(this){
    while(isEmpty())
      wait() ;
    e = buf.remove(0);
    if(isFull()){
      cursize--;
      notify(); }
    else
      cursize--; }
  return e; }
```

*P. Joshi et al., An Effective Dynamic Analysis for Detecting Generalized Deadlocks, FSE 2010

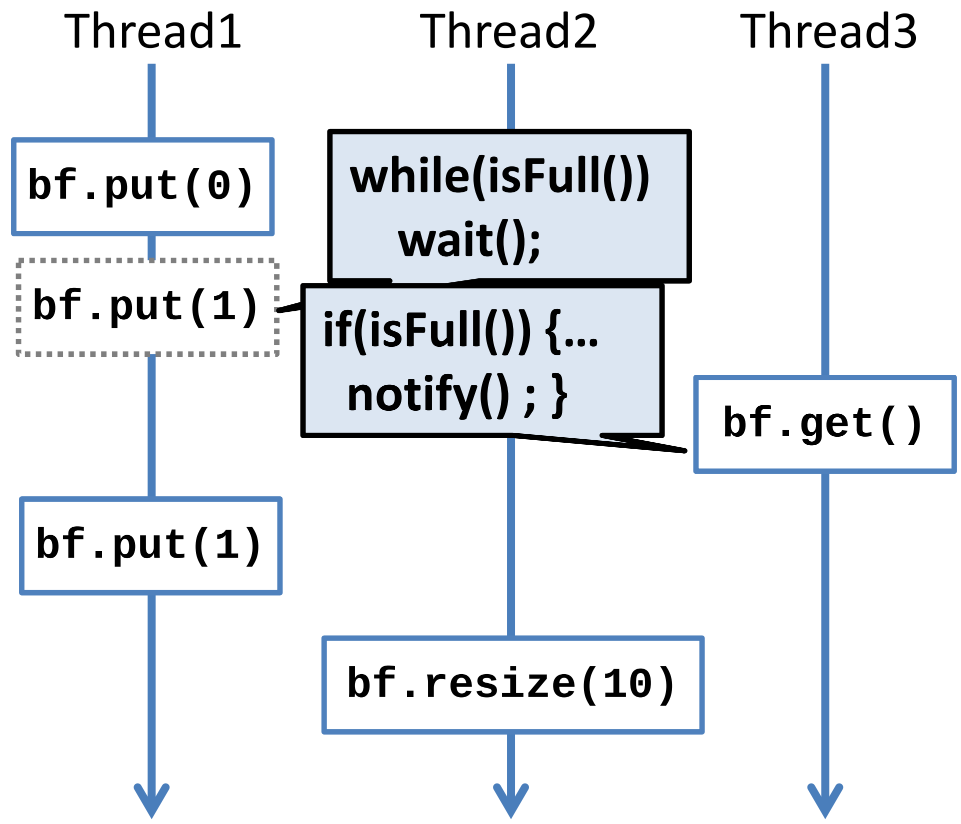
Correct Execution Scenario

```
main() {
 BoundedBuffer bf =
   new BoundedBuffer(1);
 (new Thread1(bf)).start();
 (new Thread2(bf)).start();
 (new Thread3(bf)).start();}

Thread1(BoundedBuffer bf){
  bf.put(0);
  bf.put(1);}

Thread2(BoundedBuffer bf){
  bf.resize(10);}

Thread3(BoundedBuffer bf){
  bf.get();}
```



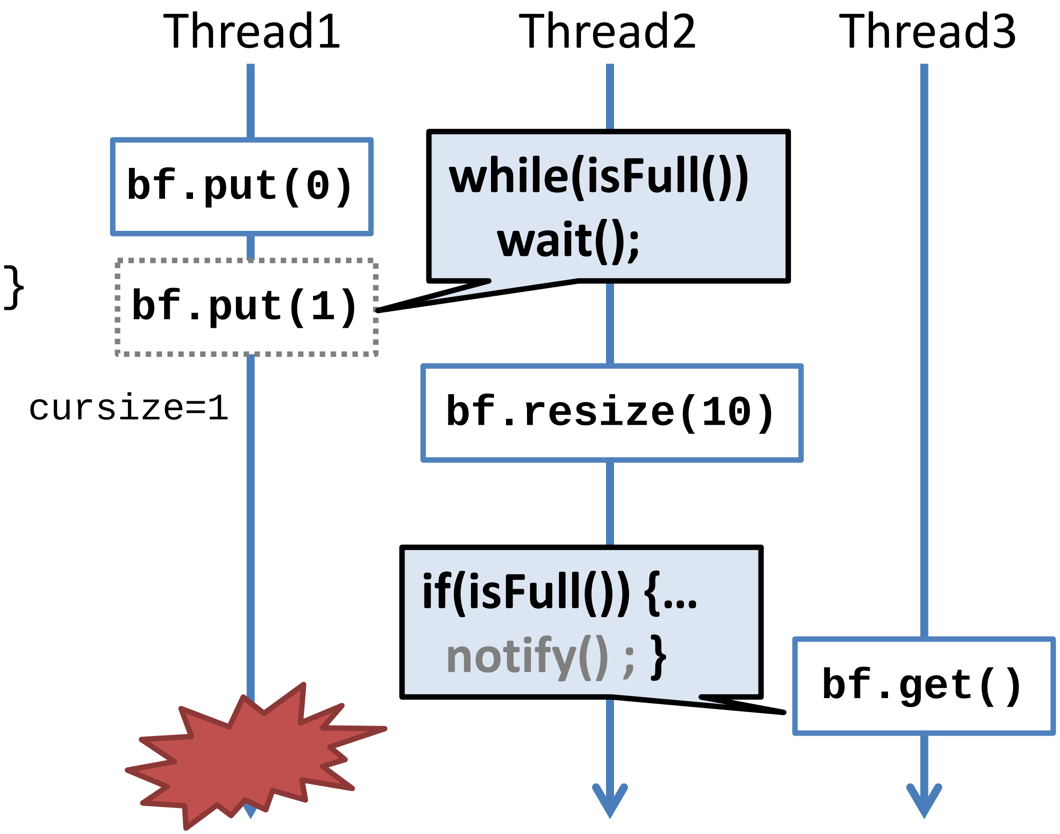
Another Correct Execution Scenario

```
main() {
 BoundedBuffer bf =
   new BoundedBuffer(1);
 (new Thread1(bf)).start();
 (new Thread2(bf)).start();
 (new Thread3(bf)).start();}

Thread1(BoundedBuffer bf){
  bf.put(0);
  bf.put(1);}

Thread2(BoundedBuffer bf){
  bf.resize(10);}

Thread3(BoundedBuffer bf){
  bf.get();}
```



Deadlock Execution Scenario

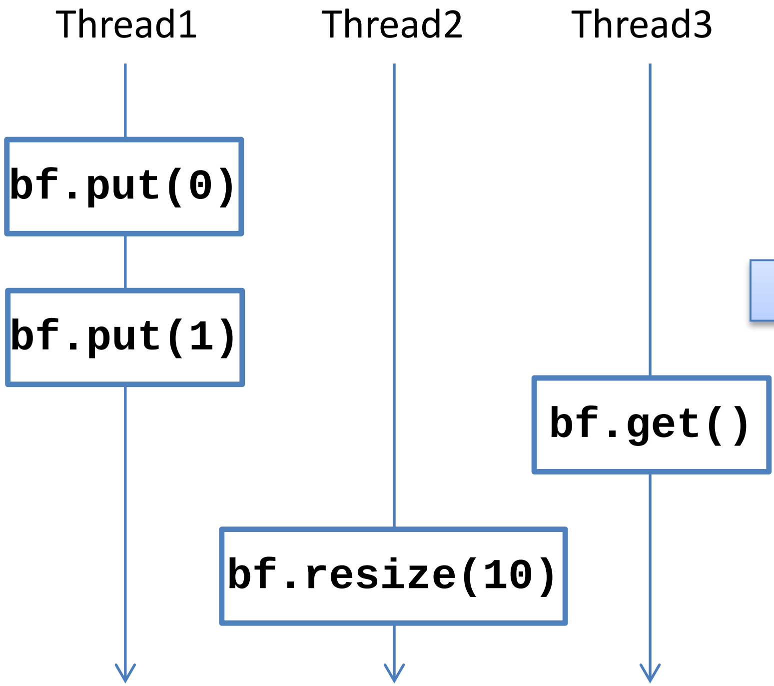
```
main() {
 BoundedBuffer bf =
   new BoundedBuffer(1);
 (new Thread1(bf)).start();
 (new Thread2(bf)).start();
 (new Thread3(bf)).start();}

Thread1(BoundedBuffer bf){
  bf.put(0);
  bf.put(1);}

Thread2(BoundedBuffer bf){
  bf.resize(10);}

Thread3(BoundedBuffer bf){
  bf.get();}
```



CHECKMATE: Trace Program Model Checking

- Observe a multi-threaded program execution
- Retain only the synchronization operations observed during execution
  - Throw away all other operations like memory update and method calls
- Create a program from the retained operations (trace program)
- Model checking trace program
  - Check partial behaviors

Trace Program Example




```
main() {
 bf = Lock();
 isFull=false;
 start(t1);
 start(t2);
 start(t3);}

t1() { bf.put(0)
 lock(bf) ;
 if(isFull)
   wait(bf) ;
 isFull=true;
 notify(bf) ;
 unlock(bf);
        bf.put(1)
 lock(bf);
  if(isFull)
   wait(bf) ;
 notify(bf);
 unlock(bf);}

t2() {bf.resize()
 lock(bf);
 isFull=false;
 unlock(bf);
}

t3() {bf.get()
 lock(bf) ;
 if(isFull)
  notify(bf);
 unlock(bf);
}
```