Deadlock Detection

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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

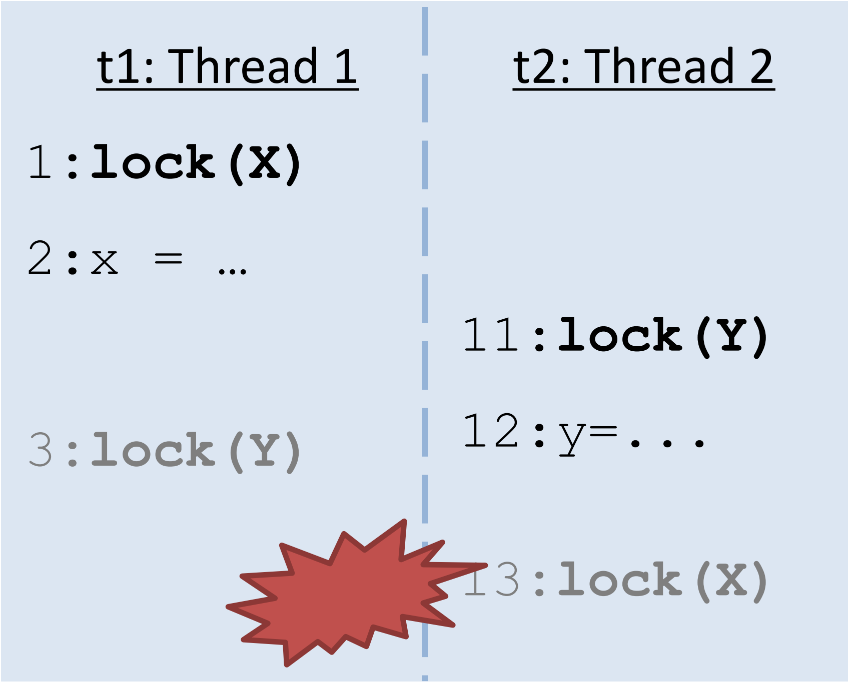
- A deadlock occurs when each of a set of threads is blocked, waiting for another thread in the set to satisfy certain condition
  - **release shared resource**
  - **raise event**

Resource Deadlock 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)
}
```



Communication Deadlock

- Lost notify

```
   Thread1() {                      Thread2() {
1:  ...                          11:  ...
2:  for(i=0;i<10;i++){           12:  for(j=0;j<10;j++){
3:    wait(m) ;}                 13:    notify(m);}
   }                                }
```

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

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

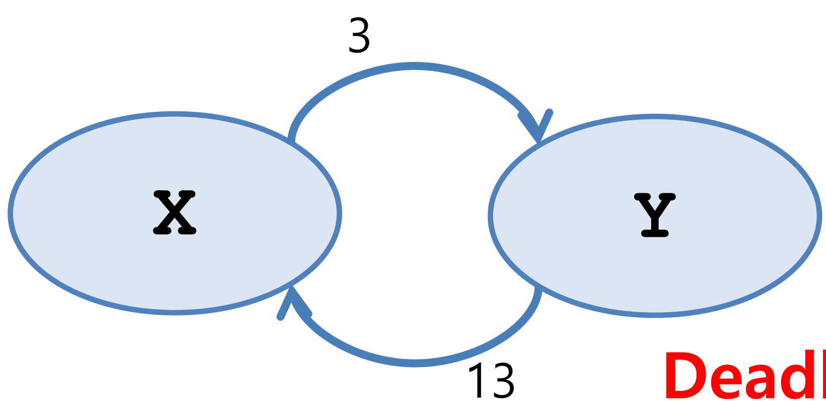
→ Report deadlock when the graph has any cycle

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)`
	`12:b=...`
`3:lock(Y)`	
	`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

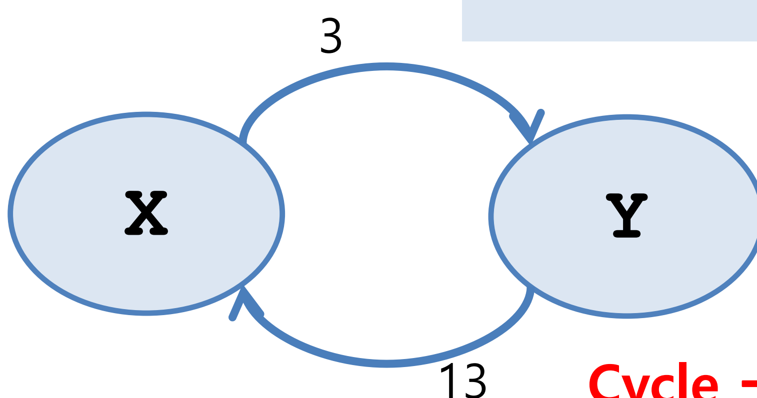
[Harrow, SPIN 00] J. J. Harrow, Jr.: Runtime checking of multithreaded applications with Visual Threads, SPIN Workshop 2000

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

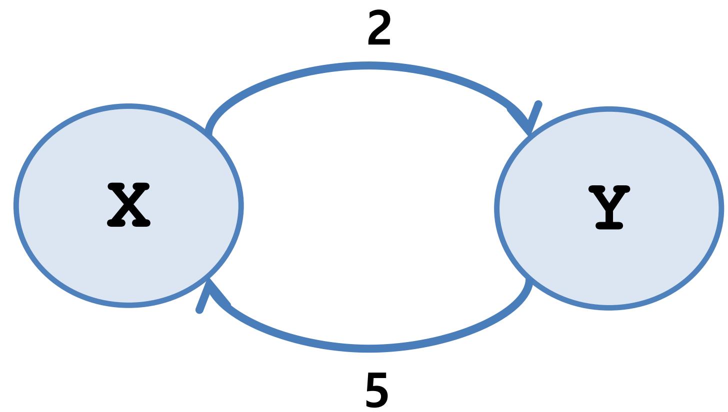
False Positive Example#1 – Single Thread Cycle

```
   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

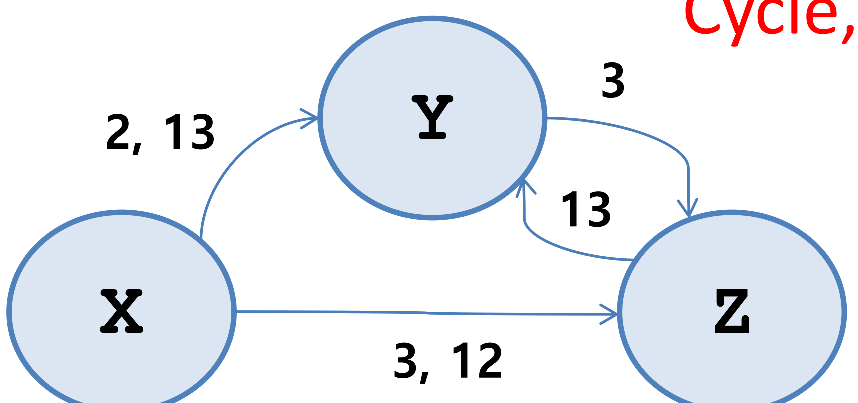
A cycle that consists of edges created by one thread is a false positive

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

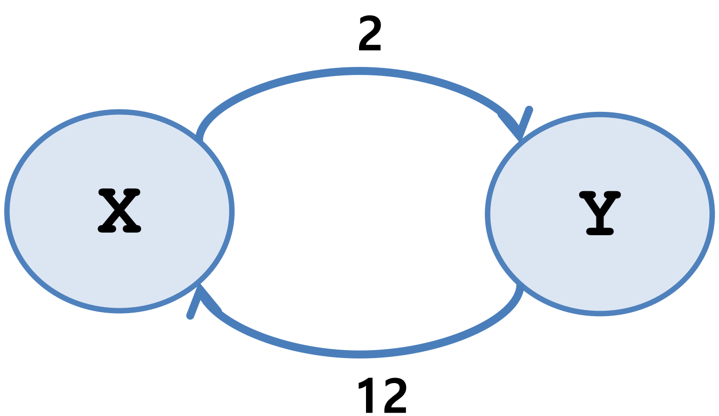
```
main(){
0:   start(f1);
 }
```

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

Thread segment#1 (lines 1–4)

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

Thread segment#2 (lines 11–14)



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*

- 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

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