Synchronization: Deadlocks

ICS332
Operating Systems

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Deadlocks

- The previous set of lecture notes talked about race conditions
- In these lecture notes we talk about another common bug that can happen in concurrent programs: deadlocks
    - This is a very different kind of bug
    - Often not as confusing / difficult to deal with as race conditions
- Basically, when you write concurrent code, the main advice is “beware of race conditions, and beware of deadlocks”

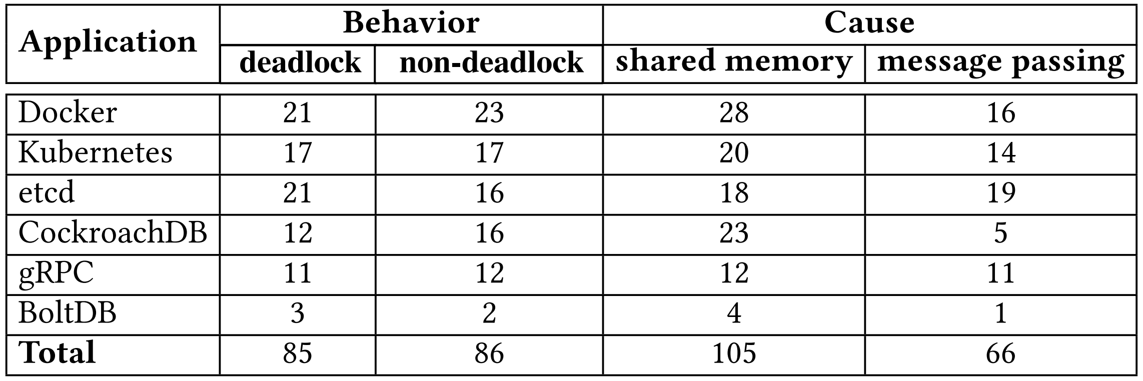
- Deadlocks are pretty common and researchers have looked at open-source software and git logs to see how often they occur
- Let’s look at a couple of such empirical results…

Deadlocks in the Wild

[Learning from Mistakes: A Comprehensive Study on Real-World Concurrency Bug Characteristics, Lu et al., ASPLOS'08]

Application	Fraction of Concurrency Bugs that are Deadlocks
MySQL (database server)	8%
Apache (web server)	23%
Mozilla (web browser)	28%
OpenOffice (office suite)	25%
Overall	29%

[Understanding Real-World Concurrency Bugs in Go, Tu et al., ASPLOS'19]



Application	Behavior		Cause	
	deadlock	**non-deadlock**	**shared memory**	**message passing**
Docker	21	23	28	16
Kubernetes	17	17	20	14
etcd	21	16	18	19
CockroachDB	12	16	23	5
gRPC	11	12	12	11
BoltDB	3	2	4	1
Total	85	86	105	66

Table 5. Taxonomy. *This table shows how our studied bugs distribute across different categories and applications.*

Deadlocks

- The name is inspired from real-life situations
- Early 20th Century Kansas legislature proposed bill: ”When two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone”
  - Likely not true

A video of this happening

The Classic 2-Lock Example

Thread #1

```
. . .
lock1.lock();
. . .
lock2.lock();
. . .
```

Thread #2

```
. . .
lock2.lock();
. . .
lock1.lock();
. . .
```

The Classic 2-Lock Example

Thread #1
`. . .`
`lock1.lock();`
`. . .`
`lock2.lock();`
`. . .`

Thread #2
`. . .`
`lock2.lock();`
`. . .`
`lock1.lock();`
`. . .`

One possible Execution timeline

```
. . .
lock1.lock(); // Thread #1 acquires lock #1
<context switch to Thread #2>
. . .
lock2.lock(); // Thread #2 acquires lock #2
. . .
lock1.lock(); // Thread #2 is STUCK because lock #1 is taken
<context switch to Thread #1>
. . .
lock2.lock(); // Thread #1 is STUCK because lock #2 is taken
```

Both threads are waiting on each other: they are "deadlocked"

Deadlock Meme

IMPERIAL COLLEGE OF E ERING NEW
AMPUS PLAC
Explain Deadlock, and we'll hire you.
Hire me, and I'll explain it to you.
let's discuss the salary.

Defining a Deadlock

- The deadlock problem can be formalized in a very general manner
- We have a system with Resources and Processes
- The Resources:
  - There can be resources of types: R1, R2, . . ., Rm
  - There are multiple resource of each type: e.g., 3 NICs, 4 disks
- The Processes (or Threads):
  - P1, P2, ..., Pn
  - Each process can:
    - Request a resource of a given type and block/wait until one resource instance of that type becomes available
    - Use a resource
    - Release a resource
- In the previous slides we have two processes, P1 and P2 (2 threads), two resource types R1 (one lock, which corresponds to some resource), and R2 (another lock, which corresponds to another resource)
  - These “resources” could be data structures

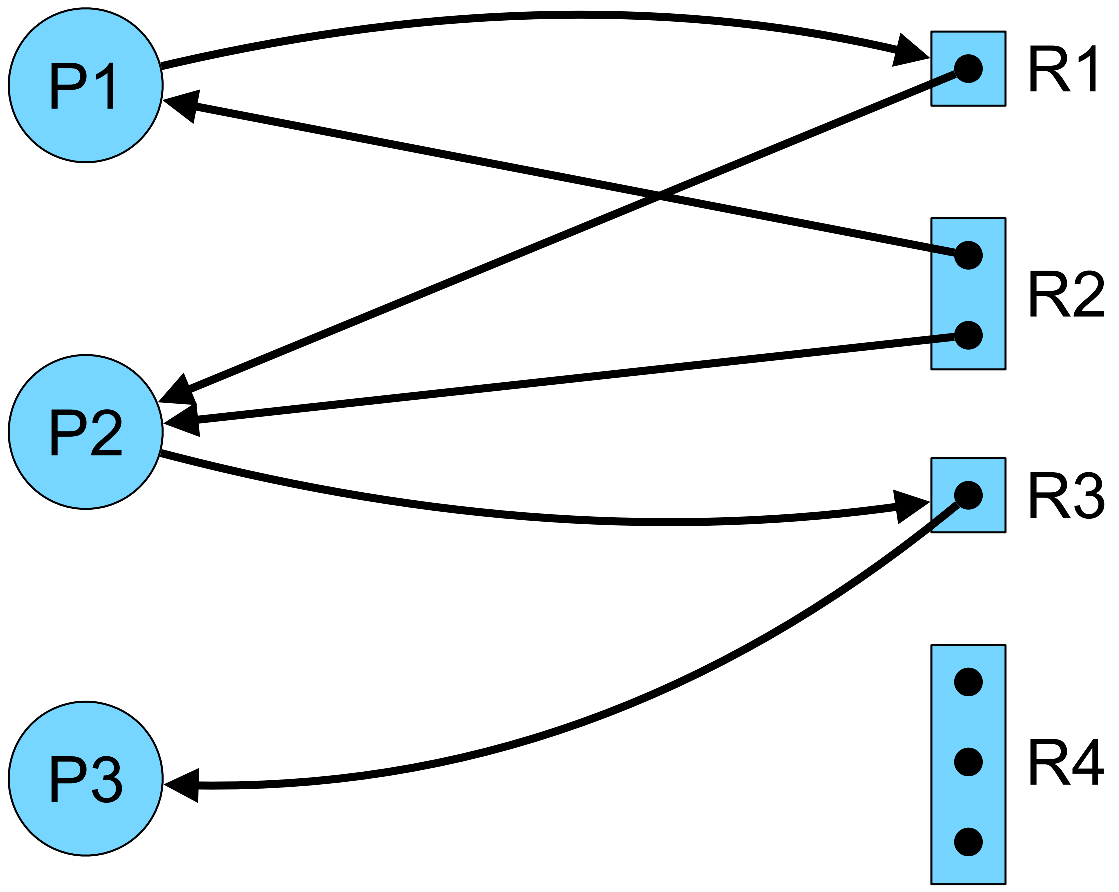
Deadlock State

- A deadlock state happens if every process is waiting for a resource instance that is being held by another process
- Three **necessary** conditions for a deadlock to occur:
  - Mutual exclusion: At least one resource is non-shareable: at most one process at a time can use it
    - In our example: the locks are mutually exclusive
  - No preemption: Resources cannot be forcibly removed from processes that are holding them
    - In our example: only the thread holding a lock can release it
  - Circular wait: There exists a set {P0,P1,...,Pp} of waiting processes such that ($\forall i \in \{0, 1, ...p - 1\}$) Pi is waiting for a resource held by Pi +1 and Pp is waiting for a resource held by P0
    - i.e., There is a circular chain of processes such that each process holds one or more resources that are being requested by the next process in the chain
    - In our example: P1 has lock1 and needs lock2, and P2 has lock2 and needs lock1
- If your program is in a state that meets all three conditions, then it **may** deadlock, otherwise you're safe

Resource Allocation Graph

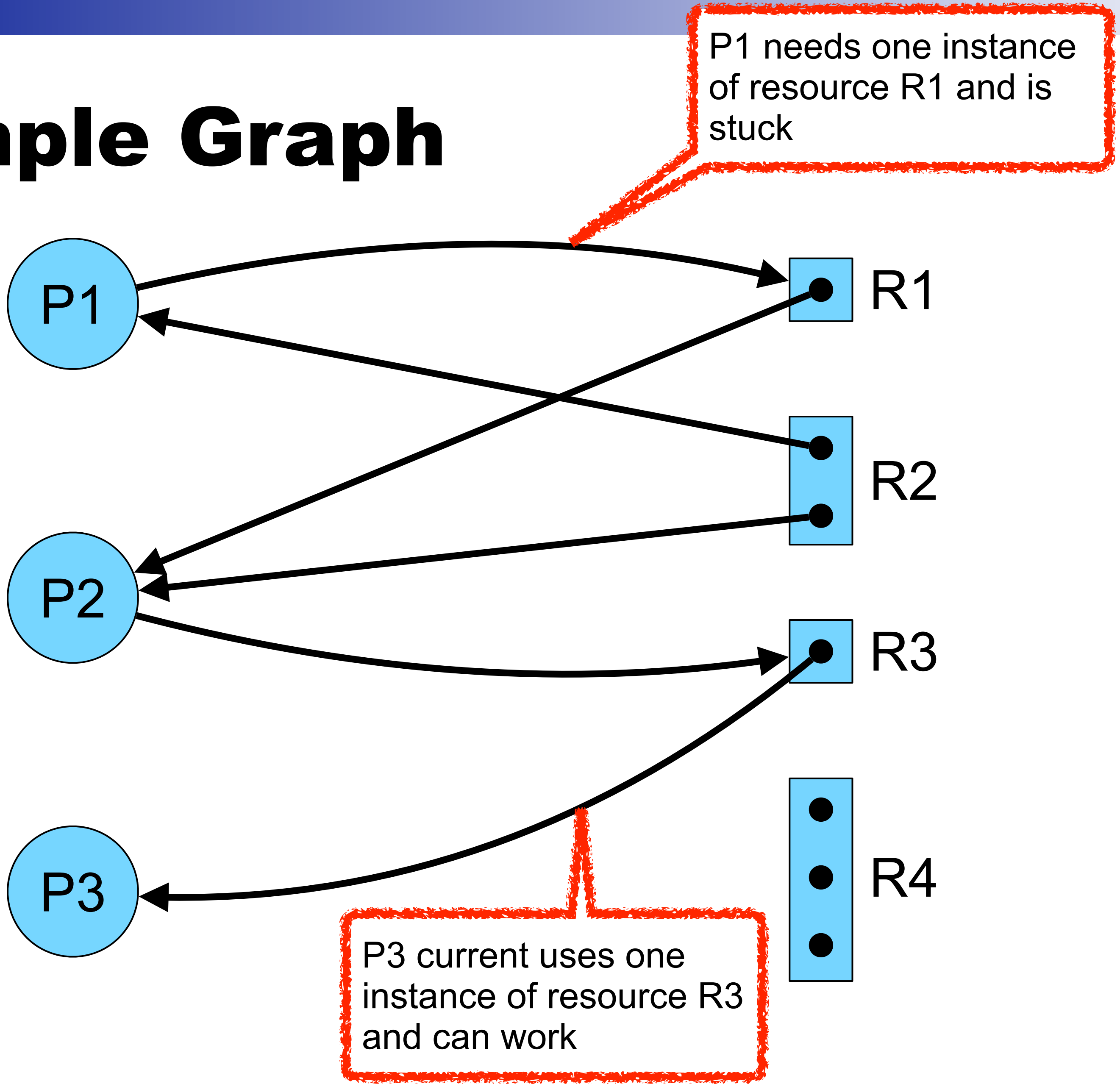
- Describing the system can be done precisely and easily with a resource-allocation-request graph, where
- The set of vertices is made of:
  - The set of processes {P0, P1, ..., Pn}, and
  - The set of resource types {R0, R1, ..., Rm}
    - Each resource instance is a black dot
- The set of directed edges is made of:
  - Request edges where a request edge is built from a process Pi to a resource Rj if Pi has requested a resource of type Rj
  - Assignment edges where an assignment edge is built from an instance of a resource type Rj to a process Pi if Pi holds a resource instance of type Rj
- Note: if a request can be fulfilled, the assignment edge replaces immediately the request edge
- Let’s see it on a picture…

Example Graph



Example from Operating Systems Concepts textbook, Silberschatz et al.

Example Graph


P1 needs one instance of resource R1 and is stuck
P1
P2
P3
R1
R2
R3
R4
P3 current uses one instance of resource R3 and can work

Example from Operating Systems Concepts textbook, Silberschatz et al.

Cycles in the Graph

- Theorem:
  - If the resource-allocation-request graph contains no (directed) cycle, then there is no deadlock in the system
  - If the graph contains a cycle then there **may** be a deadlock
- **If there is only one resource instance** (black dot) per resource type then we have a Stronger Theorem:
  - The existence of a cycle is a necessary and sufficient condition for the existence of a deadlock
- Let’s draw the graph for our 2-thread/2-lock examples…..

2-Thread/2-Lock examples

Thread #1

```
. . .
lock1.lock();
. . .
lock2.lock();
. . .
```

Thread #2

```
. . .
lock2.lock();
. . .
lock1.lock();
. . .
```

Thread #1
Thread #2
Lock #1
Lock #2

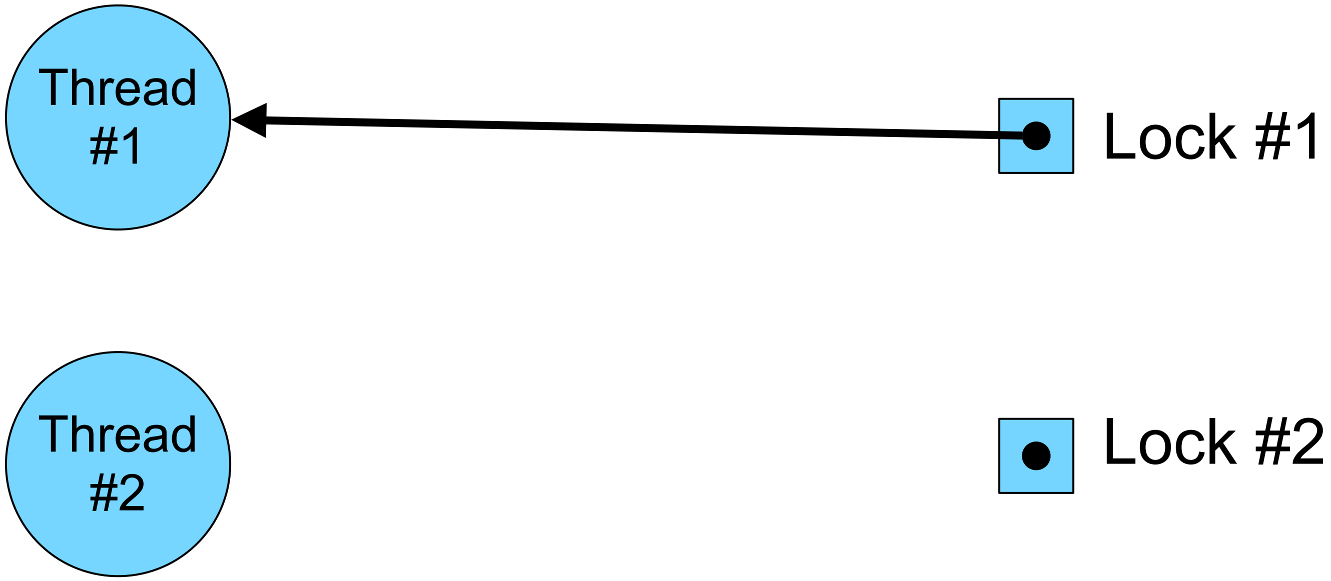
2-Thread/2-Lock examples

Thread #1

```
. . .
lock1.lock();
. . .
lock2.lock();
. . .
```

Thread #2

```
. . .
lock2.lock();
. . .
lock1.lock();
. . .
```



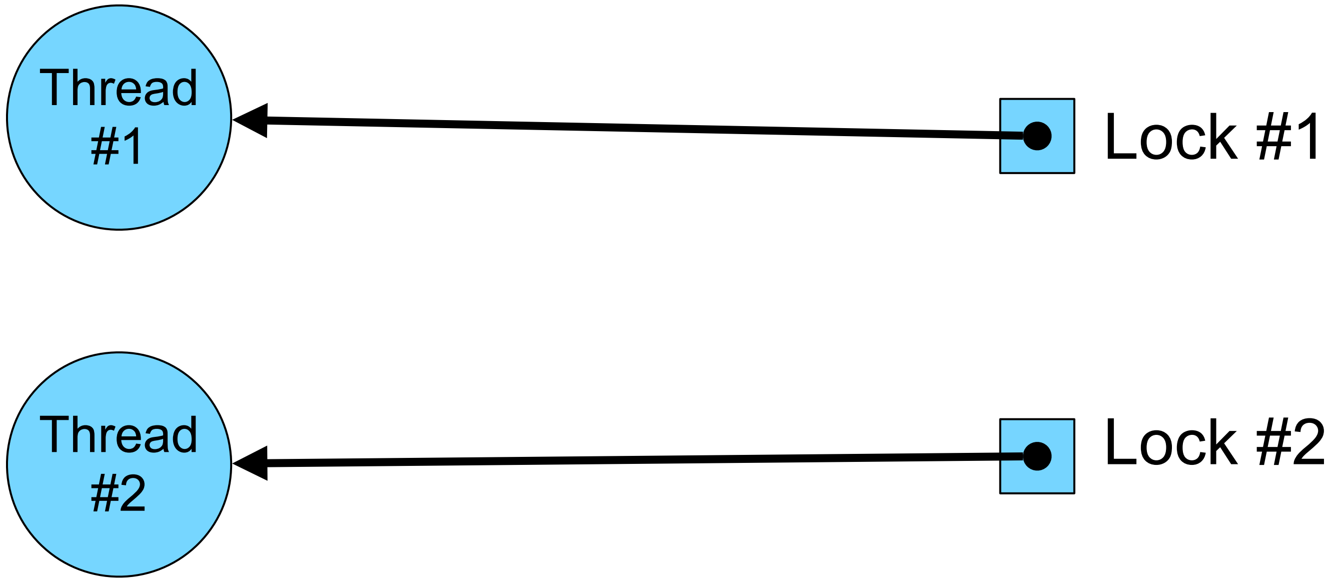
2-Thread/2-Lock examples

Thread #1

```
. . .
lock1.lock();
. . .
lock2.lock();
. . .
```

Thread #2

```
. . .
lock2.lock();
. . .
lock1.lock();
. . .
```



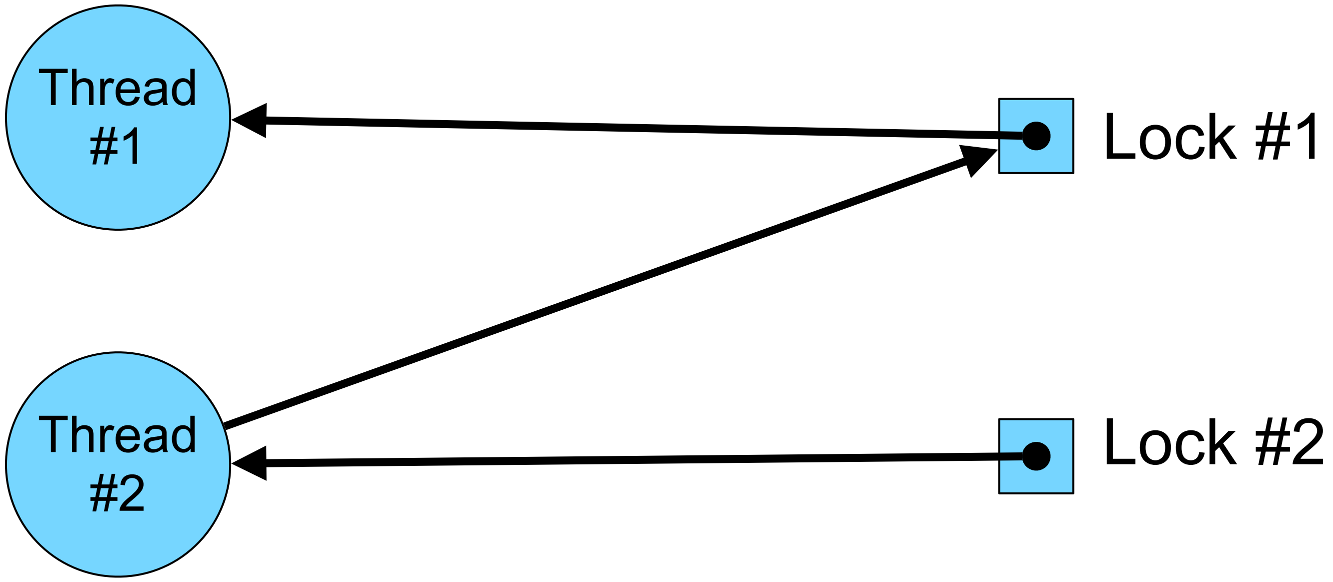
2-Thread/2-Lock examples

Thread #1

```
. . .
lock1.lock();
. . .
lock2.lock();
. . .
```

Thread #2

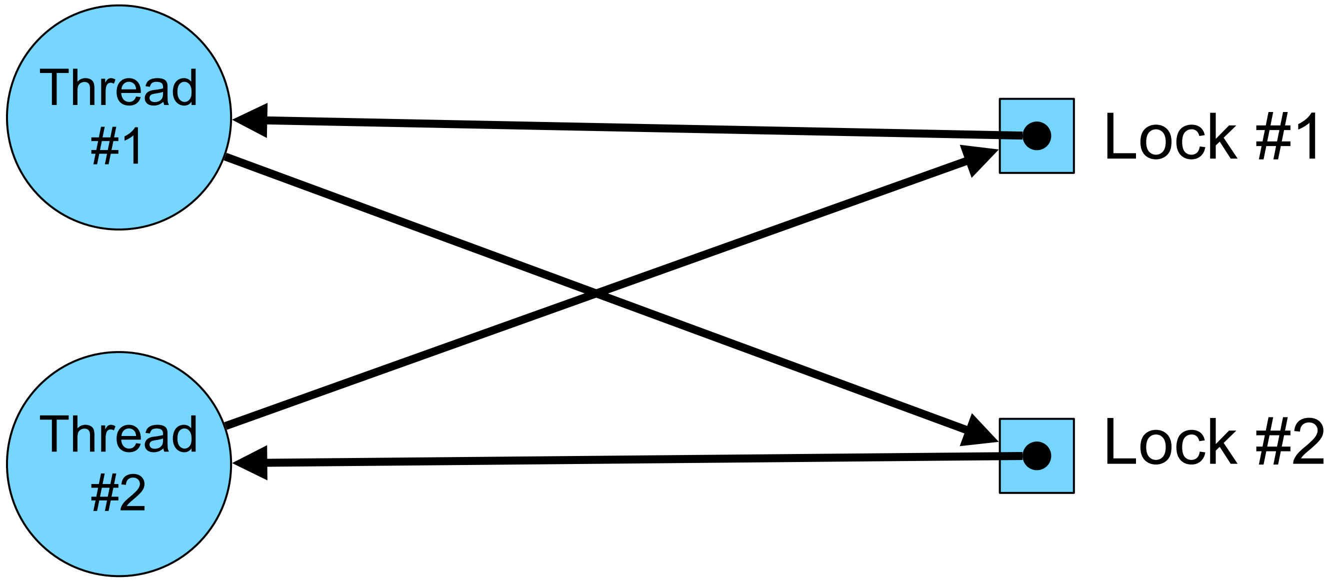
```
. . .
lock2.lock();
. . .
lock1.lock();
. . .
```



2-Thread/2-Lock examples

Thread #1	Thread #2

`. . .`
`lock1.lock();`
`. . .`
`lock2.lock();`
`. . .`
	`. . .`
	`lock2.lock();`
	`. . .`
	`lock1.lock();`
	`. . .`



Let’s move vertices around for better visibility….

2-Thread/2-Lock examples

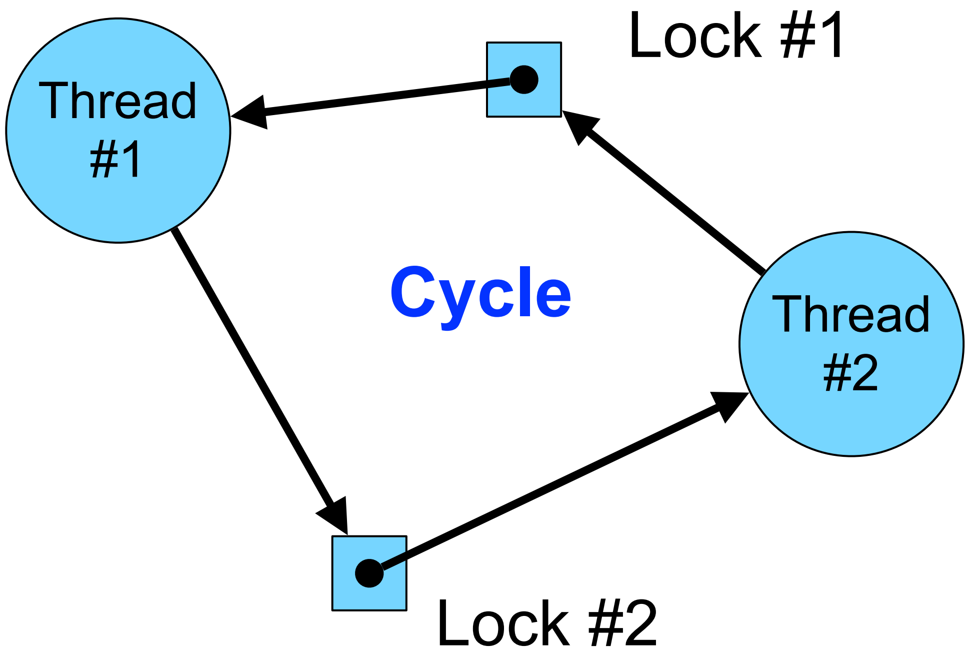
Thread #1

```
. . .
lock1.lock();
. . .
lock2.lock();
. . .
```

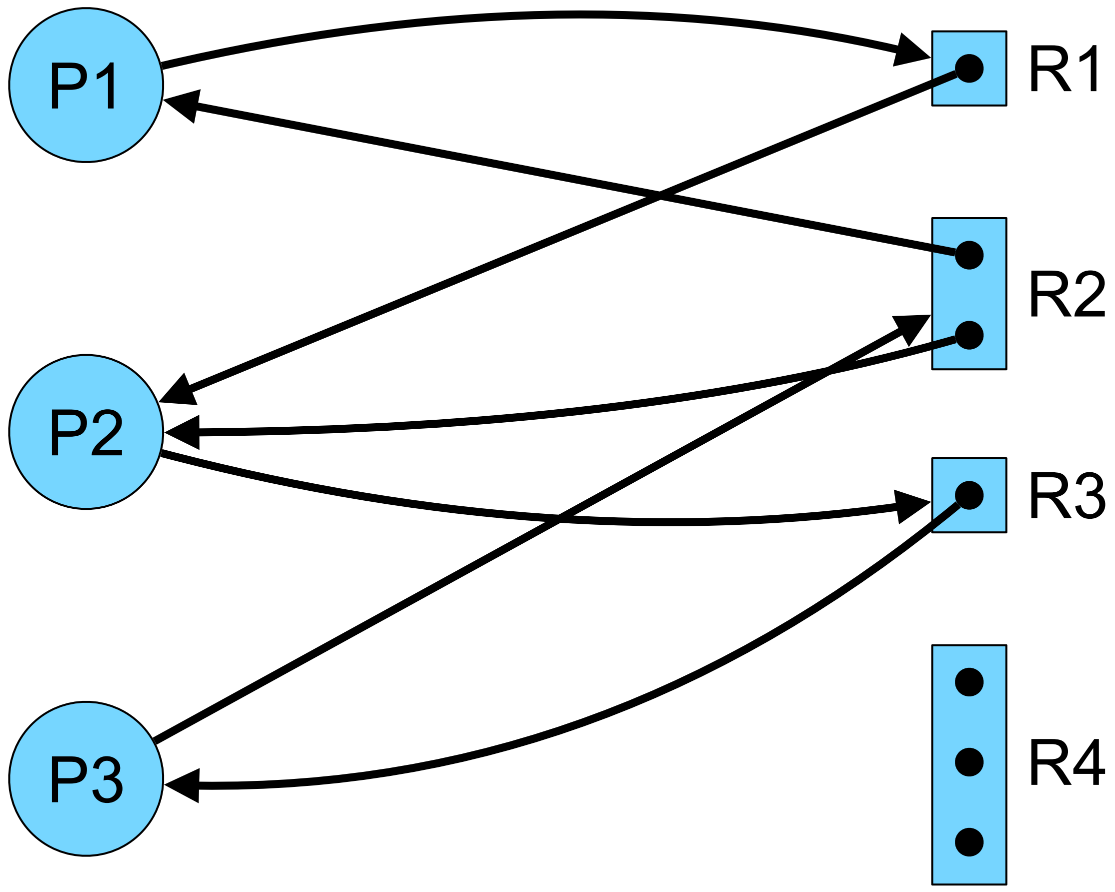
Thread #2

```
. . .
lock2.lock();
. . .
lock1.lock();
. . .
```

- We have a cycle
- There is one instance of each resource type
- There is a cycle
- The (stronger) theorem says: we are deadlocked!



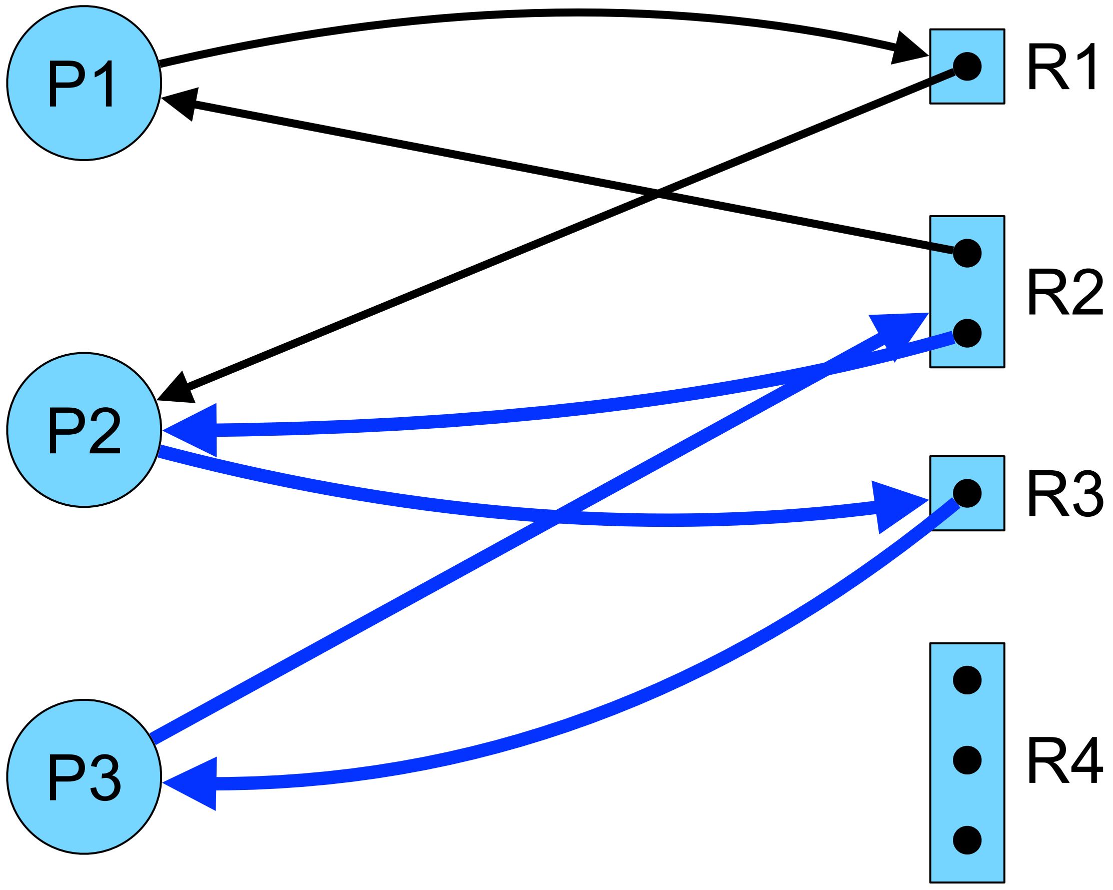
Example Graph: Cycle?



Example from Operating Systems Concepts textbook, Silberschatz et al.

Example Graph: Cycle?

The blue edges form a cycle

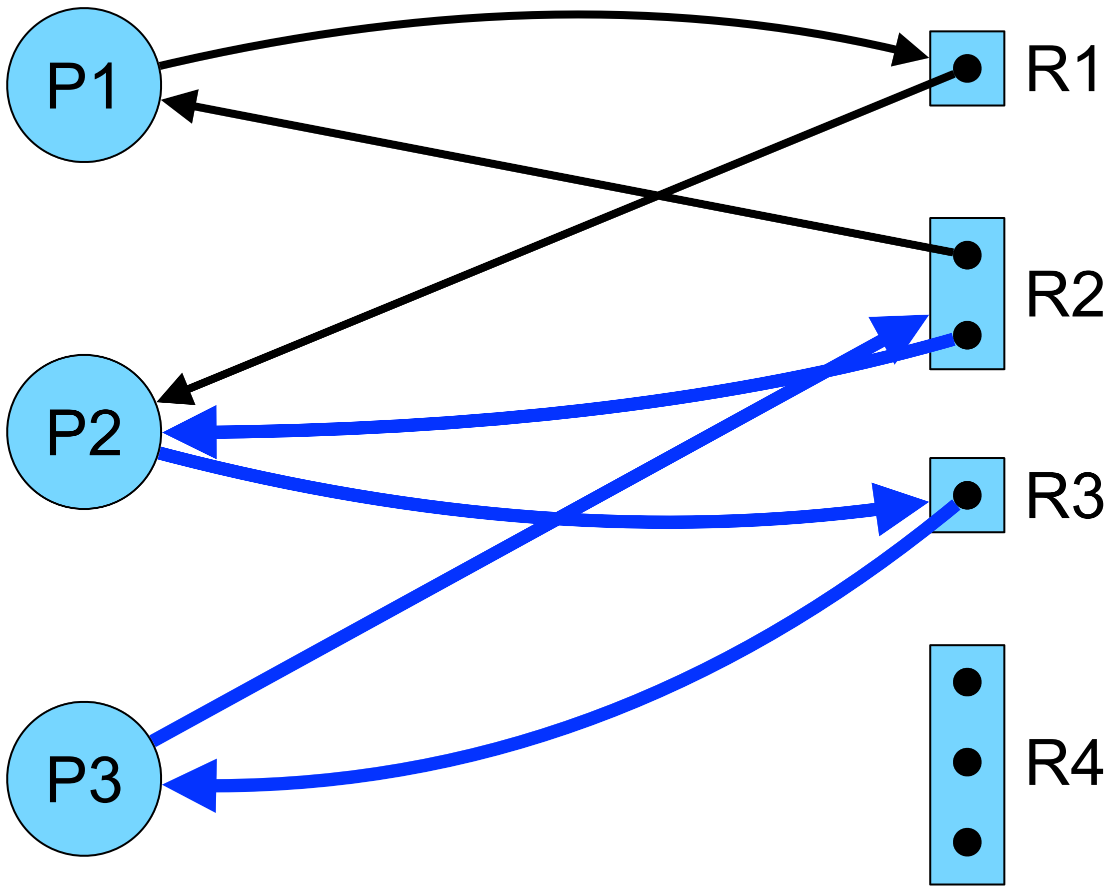


Example from Operating Systems Concepts textbook, Silberschatz et al.

Example Graph: Cycle?

The blue edges form a cycle

But are we deadlocked?



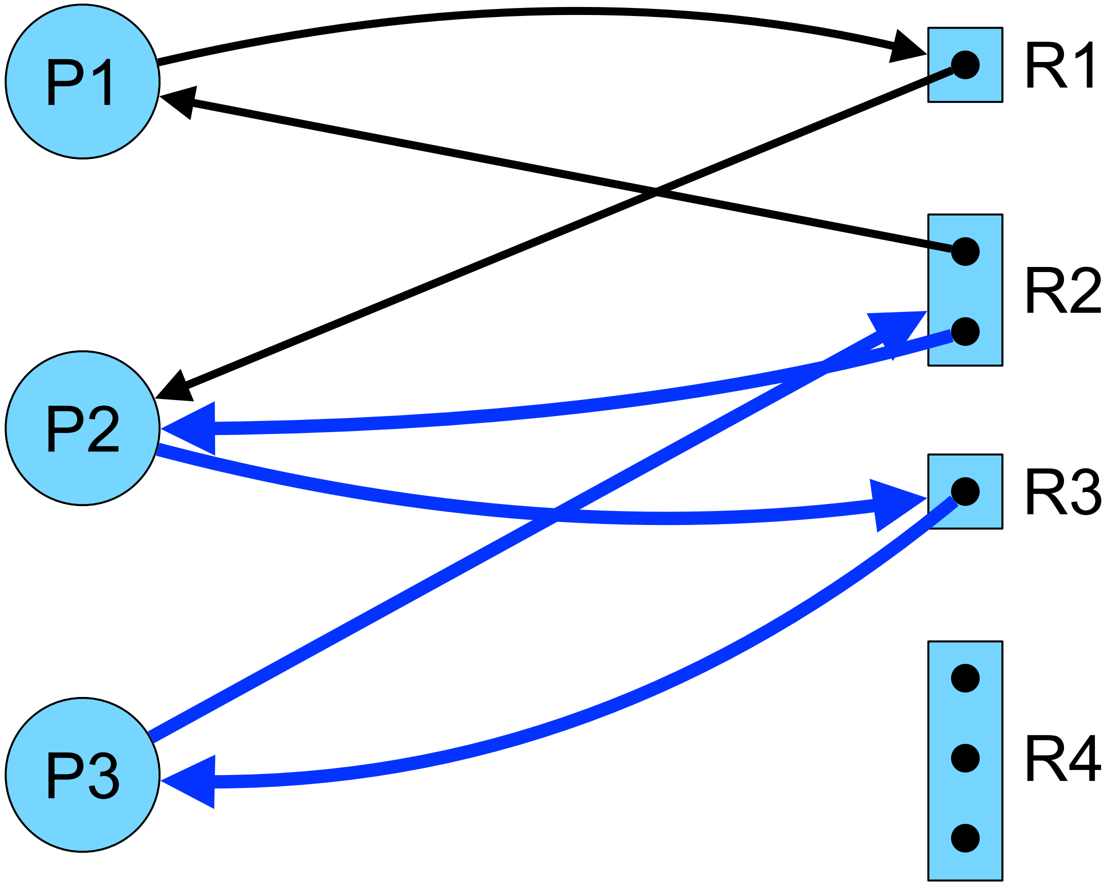
Example from Operating Systems Concepts textbook, Silberschatz et al.

Are we Deadlocked?

- In the previous example we have a cycle, so there may be a deadlock
  - Because there are multiple resources for some resource types we cannot be sure
- We have a deadlock if no process involved in the cycle can make progress
- We can check if progress as follows:
  - Each process that has all the resources it wants will eventually move on and release its resources
  - So we can remove its incoming resource allocation edges, and perhaps transform some resource request edges into resource allocation edges
  - We keep going…
- Let’s look at the example again…

Example Graph: Cycle?

The blue edges form a cycle

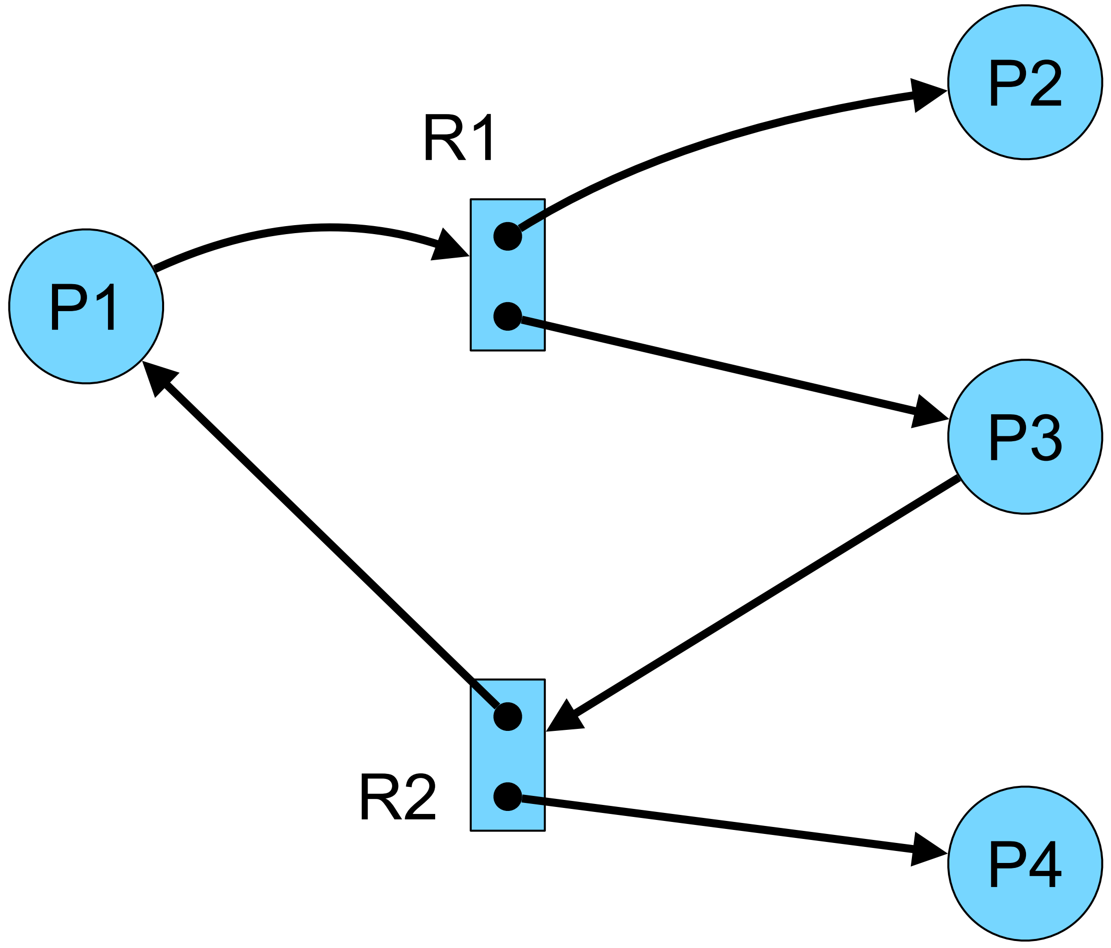


No process can make any progress due to at least one outgoing resource request edge

We have a **deadlock**

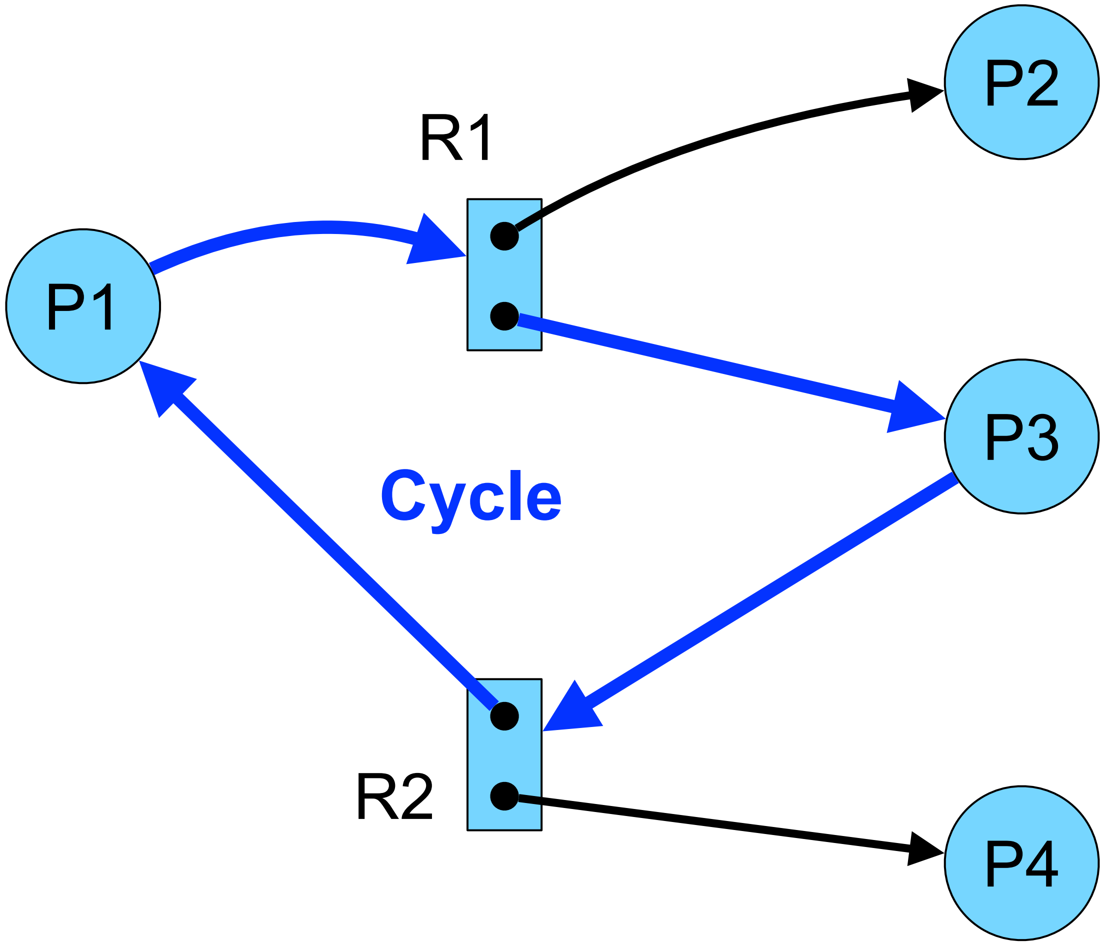
Example from Operating Systems Concepts textbook, Silberschatz et al.

Another example (1)



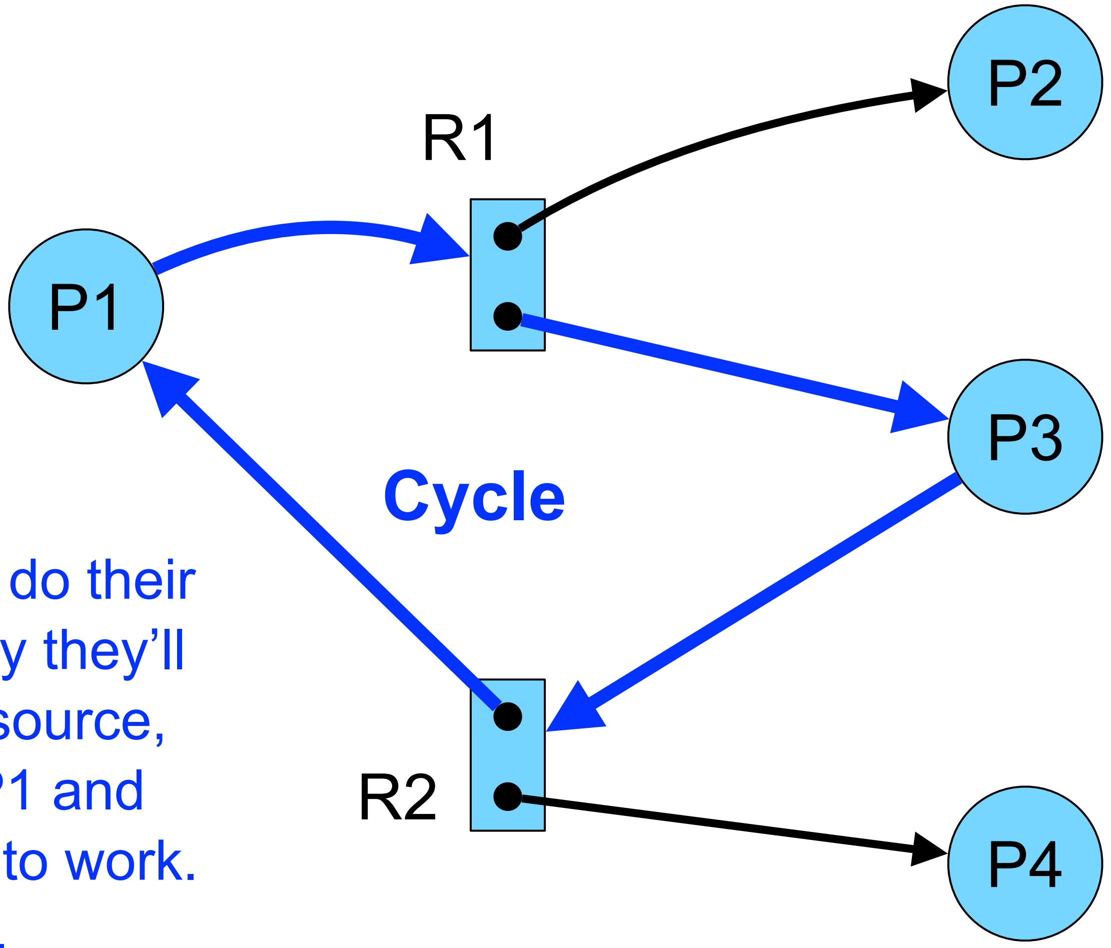
Example from Operating Systems Concepts textbook, Silberschatz et al.

Another example (2)



Example from Operating Systems Concepts textbook, Silberschatz et al.

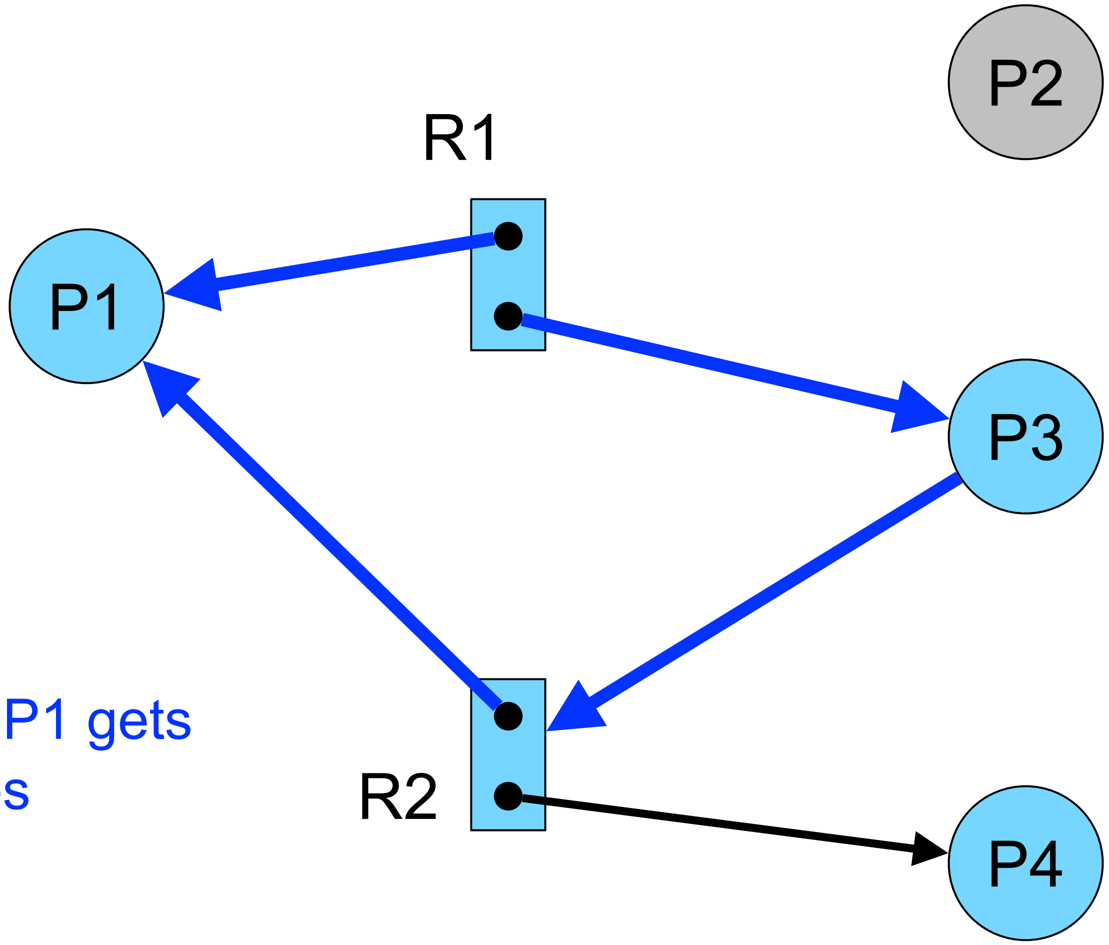
Another example (3)



P2 and P4 can do their work, eventually they'll release one resource, which means P1 and P3 will be able to work. No deadlock….

Example from Operating Systems Concepts textbook, Silberschatz et al.

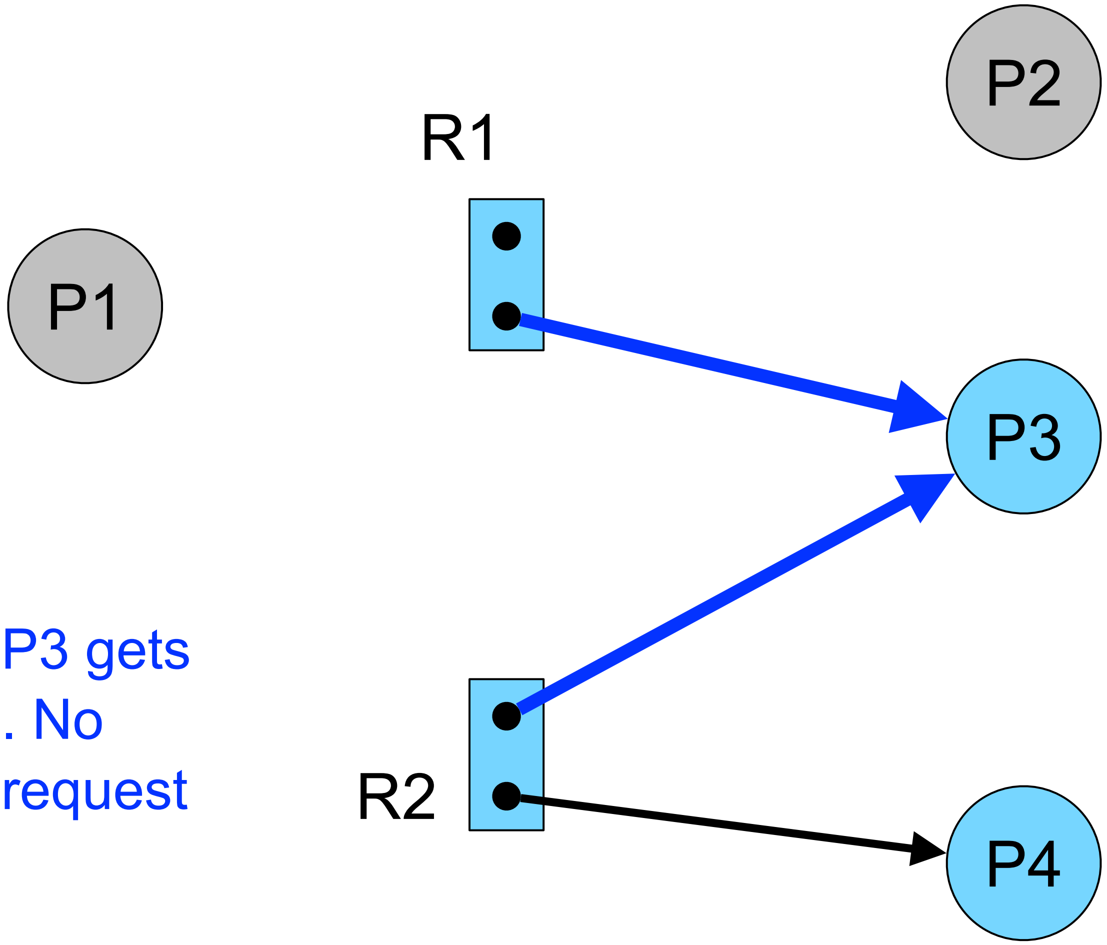
Another example (4)



P2 terminates, P1 gets its R1 resources

Example from Operating Systems Concepts textbook, Silberschatz et al.

Another example (5)



P1 terminates, P3 gets its R2 resource. No more resource request edges.

Example from Operating Systems Concepts textbook, Silberschatz et al.

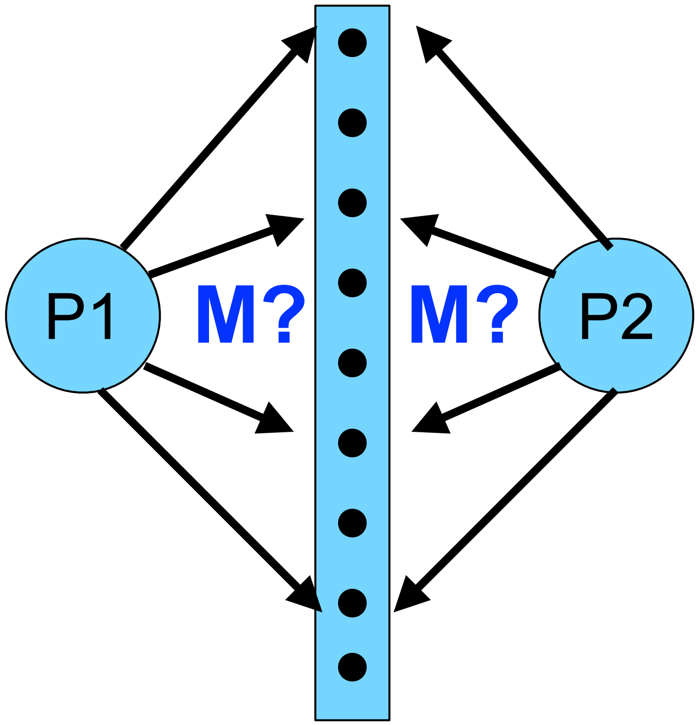
In-Class Exercise

- 9 locks
- 2 threads, each running:

```
while (true) {
   for (i=0;i < M; i++) {
      <acquire one lock>
   }

   // do something useful

   for (i=0;i < M; i++) {
      <release one lock>
   }
}
```



Question: What is the largest value of M that leads to no deadlock?

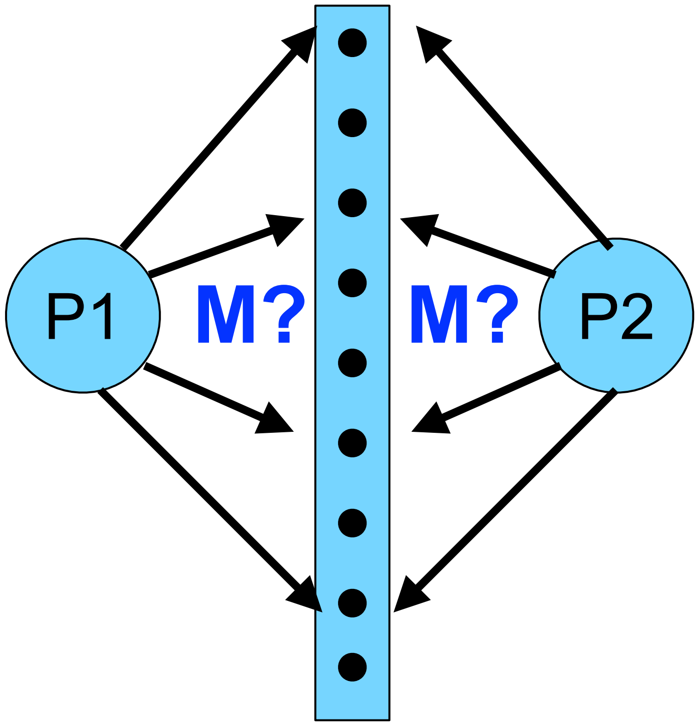
In-Class Exercise

- 9 locks
- 2 threads, each running:

```
while (true) {
   for (i=0;i < M; i++) {
      <acquire one lock>
   }

   // do something useful

   for (i=0;i < M; i++) {
      <release one lock>
   }
}
```



Answer: M=5

If both threads split the locks 4-4, which is the most “dangerous” situation, then one of them will get its 5th and last lock, and we’re ok

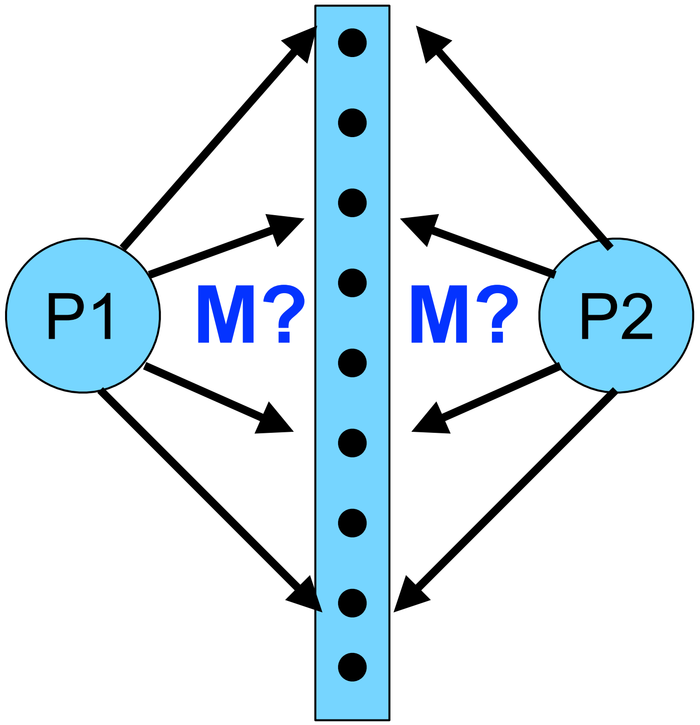
In-Class Exercise

- 9 locks
- 2 threads, each running:

```
while (true) {
   for (i=0;i < M; i++) {
      <acquire one lock>
   }

   // do something useful

   for (i=0;i < M; i++) {
      <release one lock>
   }
}
```



Deadlock for M=6

It is possible for on thread to hold 4 locks, and for the other holds 5 locks, and we're deadlocked

Strategies Against Deadlocks

- Prevention — Just build all programs so that at least one of the previous 3 necessary conditions can never be true, a by design approach
- Avoidance — If we are aware of the resources that the processes/threads will use, we could avoid deadlocks, more of a watchdog approach
- Detection and recovery — Use algorithms to detect whether a deadlock has happened and try to recover: a let’s fix it approach

Deadlock Prevention ("by design")

- Removing necessary condition #1 (Mutual Exclusion: "At least one resource is non-shareable")
  - Non-shareable resources are too useful to disallow them!
  - A critical section protected by locks, a file open for writing, etc.
- Removing necessary condition #2 (No Preemption: "Resources cannot be forcibly removed")
  - But how do we even program in an environment in which an acquired resource can be taken away at any time?
- Removing necessary condition #3 (Circular Wait)
  - This can be done, e.g., by imposing an ordering on the resources and force processes to acquire them in that order
  - The FreeBSD OS provides an order-verifier for locks (called witness)
  - Lock acquisition order is recorded, and locking locks out of order causes errors/ warnings
  - Useful, but not feasible for all programs
- **Bottom Line:** Deadlock prevention is appealing, but isn't done much at all in practice, save for a few programs that use ordered locks

Deadlock Avoidance (“watchdog”)

- One approach:
  - The OS maintain the resource-allocation-request graph at all times
  - Whenever a process requests a resource, the OS determines whether giving that resource to the process would create a cycle in the graph
  - If it would, then reject the request, otherwise, add an edge
  - In a nutshell: never add an edge that would create a cycle
  - Detecting a cycle in a graph with n vertices is usually O(n^2) (i.e., relatively expensive)
  - This approach is sometimes known as a “Graph-based Avoidance Algorithm”
- There are other approaches (e.g., see “Deadlock Avoidance via Scheduling” in OSTEP if you’re curious)

- **Bottom Line:** Deadlock avoidance is an interesting idea, but it isn’t really done in practice because too expensive

Deadlock Detection/Recovery ("let's fix it")

- Detection:
  - Use an algorithm to determine whether we're in a deadlock state
  - If only one resource (black dot) per resource type, easy
    - Build the resource-allocation-request graph, and if it has a cycle, we have a deadlock
  - If more than one resource per resource type, harder
    - Use the "fancy" Banker's Algorithm
  - This takes time, so we can only do this occasionally
- Recovery:
  - Option #1: Process termination
    - Option A: Kill all deadlocked processes
    - Option B: Kill one deadlocked process at a time until no deadlock
    - Dangerous program behaviors are then likely :(
  - Option #2: Resource preemption
    - Select a resource to be preempted
    - Rollback the process that has it (Simplest: Restart the process from scratch; Harder: "Go back till before the lock was acquired")
- **Bottom Line:** these are interesting ideas, but no OS does them because they can break applications

So what do OSes do?

- What do OSes do to help us with deadlocks???

So what do OSes do?

- What do OSes do to help us with deadlocks??? **NOTHING**
- Apparently we can live with this!?!

- Eventually, but very rarely, the deadlock may snowball until the system no longer functions and requires manual intervention (a reboot)
- But typically they remain confined to a program
- Deadlocks occur frequently-ish, and you get no help besides "make sure your code doesn't have deadlocks"
- The one good news: it's easy to tell that your code is deadlocked (it just doesn't do anything)
  - Not so with race conditions, which occur "silently"

- In the end there is no good one-size-fits-all solution, as there is no telling what kind of concurrent applications people will be developing

Priority Inversion

- A famous “OS and Deadlocks” problem
  - Assume that there are 3 processes with different priorities: L < M < H
  - H needs a resource currently held by L
  - If M becomes runnable, it will preempt L from running
  - Therefore L will never release the resource
  - And therefore H will never run
  - M has indirectly set the priority of H to the priority of L (since H has to wait for L to release the resource)
- This is called priority inversion
  - Lookup ”Mars Pathfinder priority inversion” for an interesting anecdote
- Solution → priority inheritance: If a process requesting a resource has higher priority than the process locking the resource, the process locking the resource is temporarily given the higher priority.
- This is one thing that some OSes (real-time OSes in particular) implement for you!

Main Takeaways

- Deadlocks happen when processes/threads wait indefinitely on each other to release resources (e.g., locks)
- A great way to reason about and/or visualize deadlocks of resource allocation graphs
- Three methods are possible to deal with deadlocks
  - (i) Prevention
  - (ii) Avoidance
  - (iii) Detection/Recovery
- Sadly, none of them is used much in modern OSes and you’re on your own

Conclusion

- You get no help from the OS here
- Bottom line: just be smart and develop software that does not deadlock 😬
  - The one good news: it's pretty clear to figure out that your code is deadlocked: it's stuck
- We'll have a quiz on this module next week