Deadlock

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Recap: Synchronization

- Race condition
  - A situation when two or more threads **read and write** shared data at the same time
- Critical section
  - Code sections of potential race conditions
- Mutual exclusion
  - If a thread executes its critical section, *no other threads* can enter their critical sections
- Peterson's solution
  - Software only solution providing mutual exclusion

Recap: Synchronization

- Spinlock
  - Spin on waiting
  - Use synchronization instructions (test&set)
- Mutex
  - Sleep on waiting
- Semaphore
  - Powerful tool, but often difficult to use
- Monitor
  - Powerful and (relatively) easy to use

Quiz

```
Mutex lock;
Condition full, empty;

produce (item)
{
    ______________
    while (queue.isFull())
        empty.wait(&lock);
    queue.enqueue(item);
    full.signal();
    ______________
}

consume()
{
    ______________
    while (queue.isEmpty())
        ______________
    item = queue.dequeue(item);
    ______________
    ______________
    return item;
}
```

```
Semaphore mutex = 1, full = 0,
empty = N;

produce (item)
{
    P (&empty)_________;
    P(&mutex);
    queue.enqueue(item);
    V(&mutex);
    V (&full)_________;
}

consume()
{
    P (&full)_________;
    P(&mutex);
    item = queue.dequeue();
    V(&mutex);
    V (&empty)_________;
    return item;
}
```

Quiz

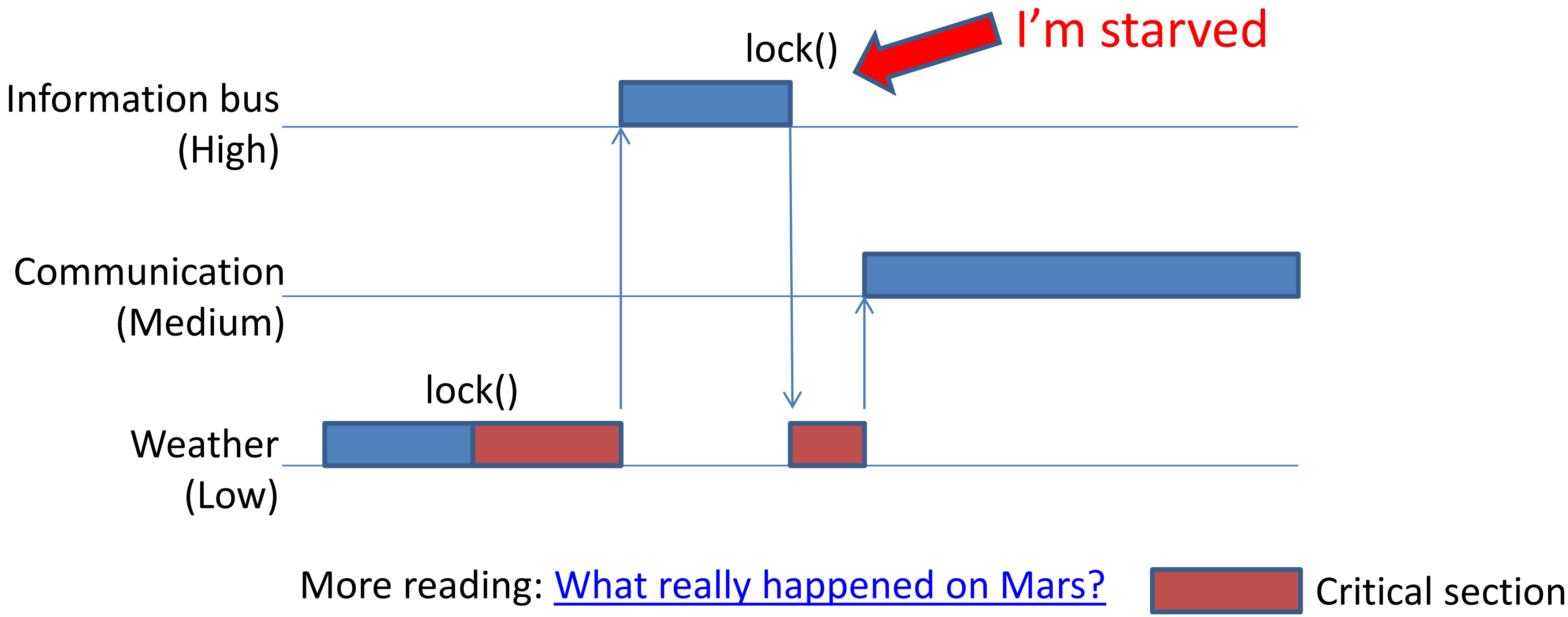
```
Mutex lock;
Condition full, empty;

produce (item)
{
    lock.acquire();
    while (queue.isFull())
        empty.wait(&lock);
    queue.enqueue(item);
    full.signal();
    lock.release();
}

consume()
{
    lock.acquire();
    while (queue.isEmpty())
        full.wait(&lock);
    item = queue.dequeue(item);
    empty.signal();
    lock.release();
    return item;
}
```

```
Semaphore mutex = 1, full = 0,
empty = N;

produce (item)
{
    P(&empty);
    P(&mutex);
    queue.enqueue(item);
    V(&mutex);
    V(&full);
}

consume()
{
    P(&full);
    P(&mutex);
    item = queue.dequeue();
    V(&mutex);
    V(&empty);
    return item;
}
```

Agenda

- Deadlock
  - Starvation vs. deadlock
  - Deadlock conditions
  - General solutions: detection and prevention
  - Detection algorithm
  - Banker's algorithm

Starvation



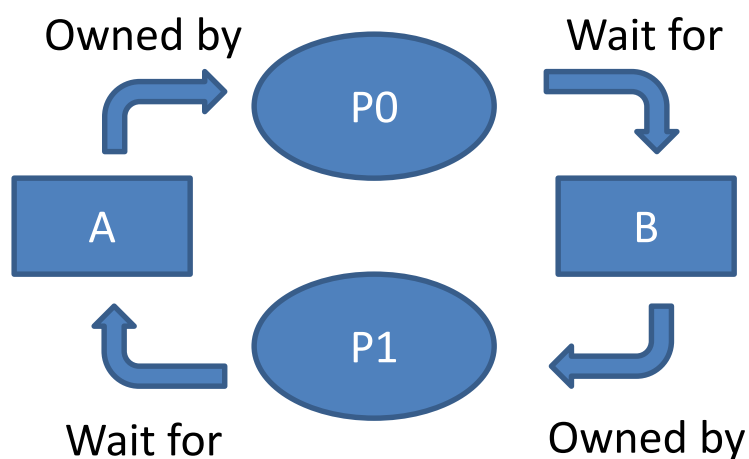
More reading: [What really happened on Mars?]

- Starvation
  - Wait potentially **indefinitely,** but it **can end**

Starvation vs. Deadlock

- Deadlock: circular waiting for resources
  - Example: semaphore A = B = 1

P0	**P1**
P(A)	P(B)
P(B)	P(A)



- Deadlock ➔ Starvation
  - But reverse is not true
  - Deadlock can't end but starvation can

Deadlock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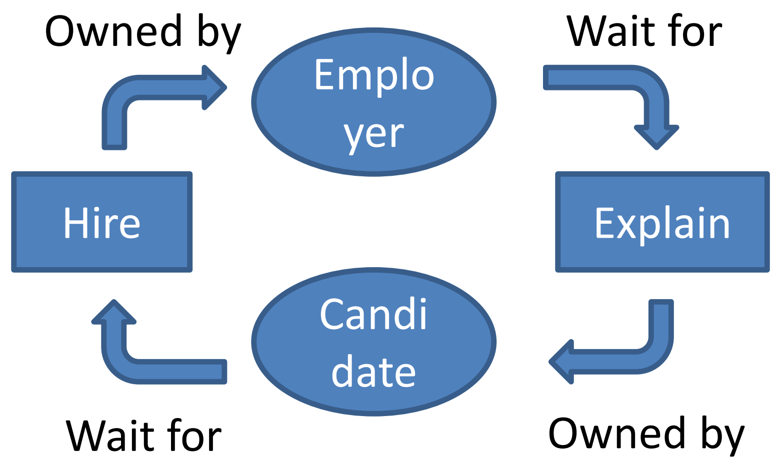
Explain Deadlock, and we'll hire you.
Hire me, and I'll explain it to you.
let's discuss the salary.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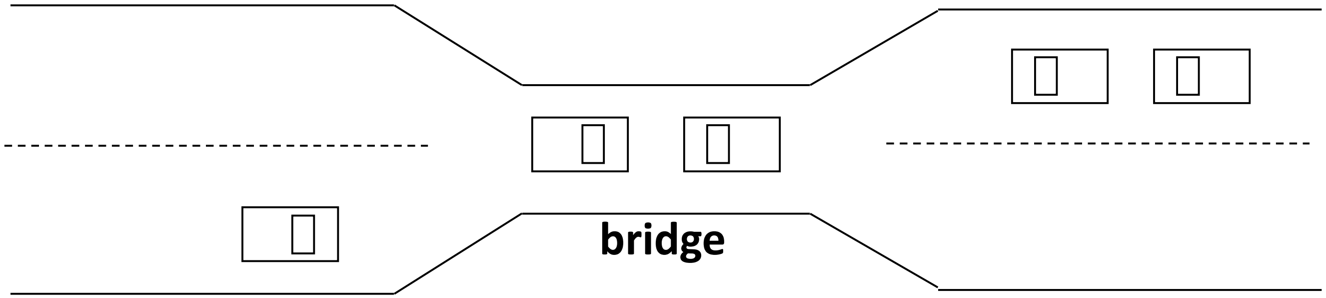
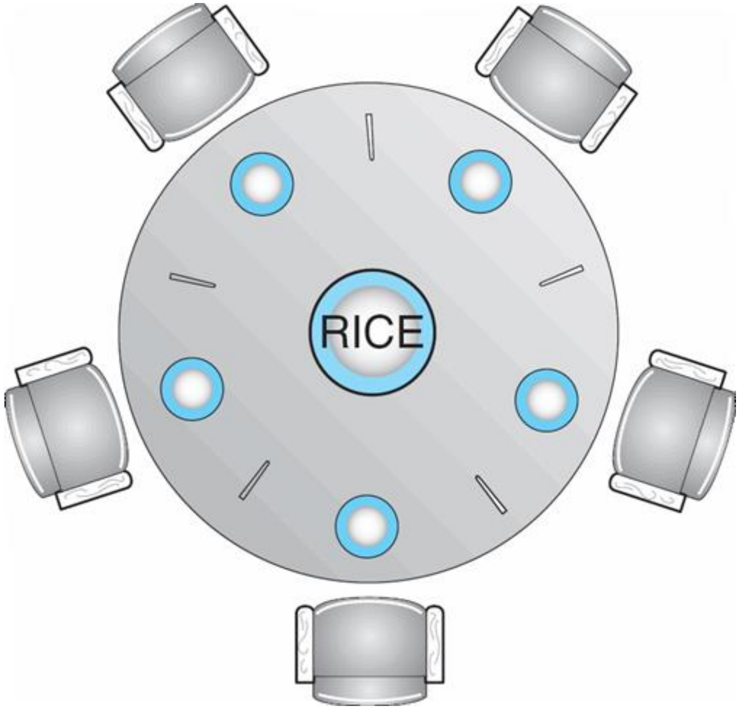
Bridge Crossing



- Traffic only in one direction
- Each section of a bridge can be viewed as a resource
- If a deadlock occurs, how to fix it?
  - Make one car backs up
  - Several cars may have to be backed up if a deadlock occurs

Dining Philosophers

- Problem synopsis
  - Need two chopsticks to eat
  - Grab one chopsticks at a time
- What happens if all grab left chopstick at the same time??
  - Deadlock!!!
- How to fix it?
- How to avoid it?



Conditions for Deadlocks

- Mutual exclusion
  - only one process at a time can use a resource
- No preemption
  - resources cannot be preempted, release must be voluntary
- Hold and wait
  - a process must be holding at least one resource, and waiting to acquire additional resources held by other processes
- Circular wait
  - There must be a circular dependency. For example, A waits B, B waits C, and C waits A.

- **All four conditions must simultaneously hold**

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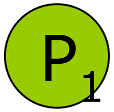
Resource-Allocation Graph

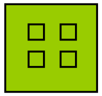
- To illustrate deadlock conditions.
- Graph consists of a set of vertices V and a set of edges E
- V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system
- request edge – directed edge $P_i \rightarrow R_j$
- assignment edge – directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph

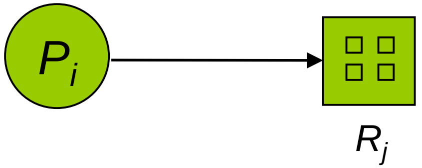
- Process



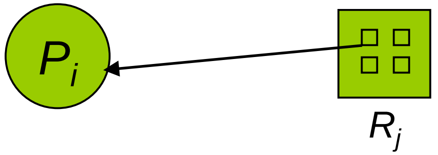
- Resource Type with 4 instances



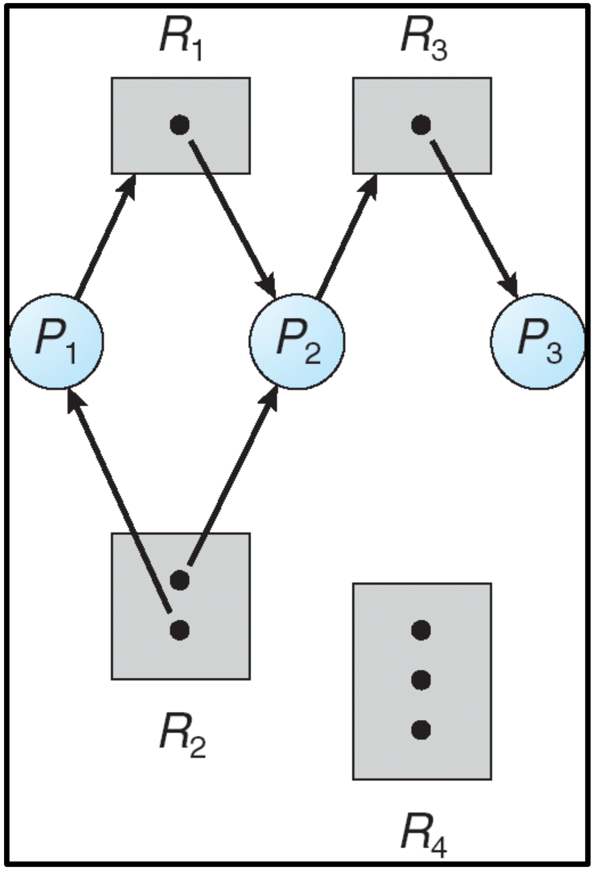
- P_i requests instance of R_j



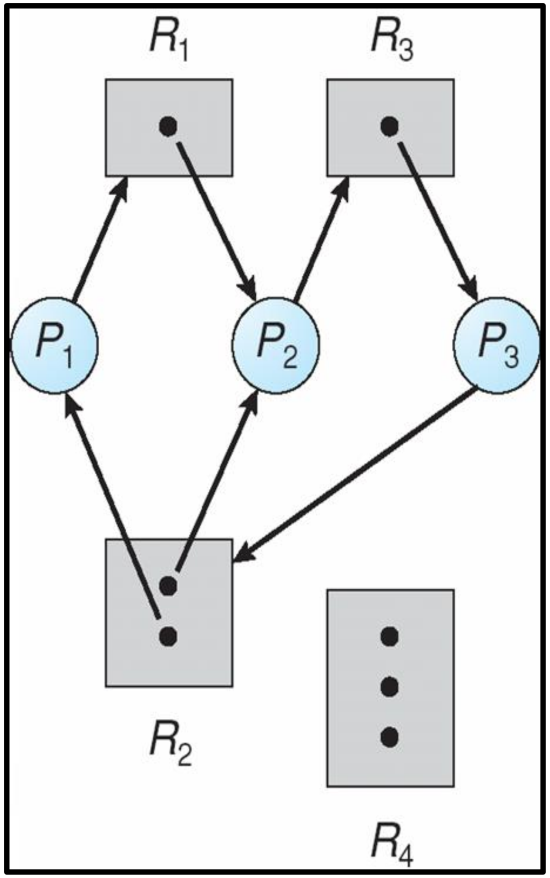
- P_i is holding an instance of R_j



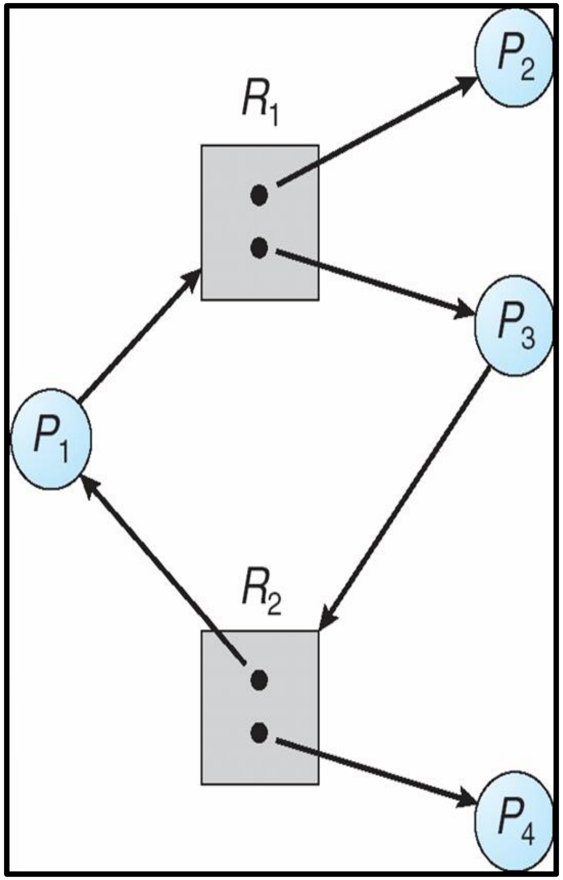
Resource Allocation Graph



Simple example



Deadlock example



With cycle, but no deadlock

- request edge – directed edge $P_i \rightarrow R_j$
- assignment edge – directed edge $R_j \rightarrow P_i$

Methods for Handling Deadlocks

- Detection and recovery
  - Allow a system to enter a deadlock and then recover
    - Need a *detection algorithm*
    - Somehow "preempt" resources
- Prevention and avoidance
  - Ensure a system never enter a deadlock
  - Possible solutions
    - have "Infinite resources"
    - prevent "hold and wait"
    - prevent "circular wait"

Recall four deadlock conditions:
(1) Mutual exclusion, (2) no preemption, (3) hold and wait, (4) circular wait

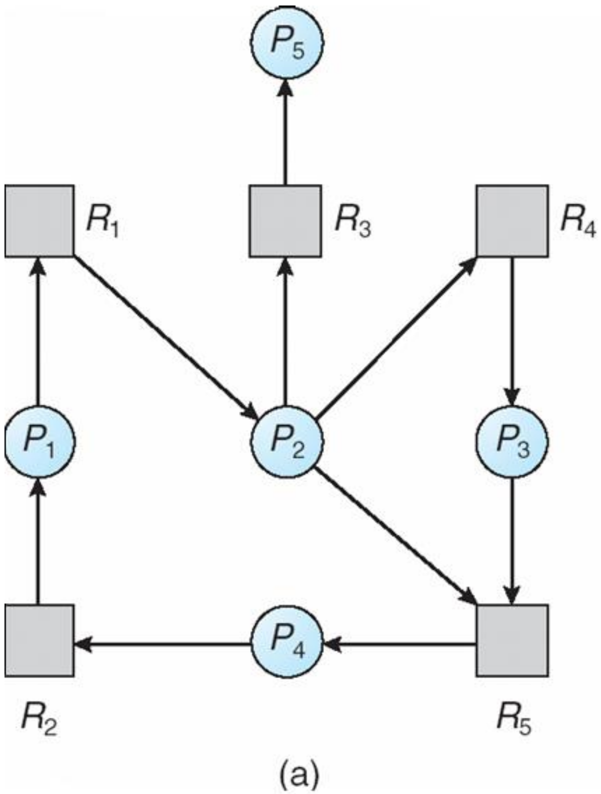
Deadlock Detection

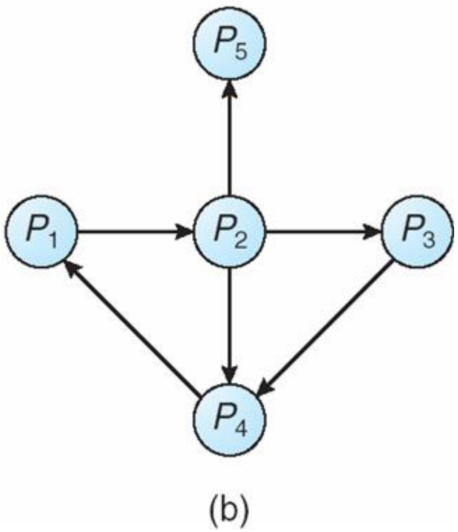
- Deadlock detection algorithms
  - Single instance for each resource type
  - Multiple instances for each resource type

Single Instance Per Resource

- Each resource is unique
  - E.g., one printer, one audio card, …
- Wait-for-graph
  - Variant of the simplified resource allocation graph
  - Remove resource nodes, collapse corresponding edges
- Detection algorithm
  - Searches for a cycle in the wait-for graph
  - Presence of a cycle points to the existence of a deadlock

Wait-for Graph

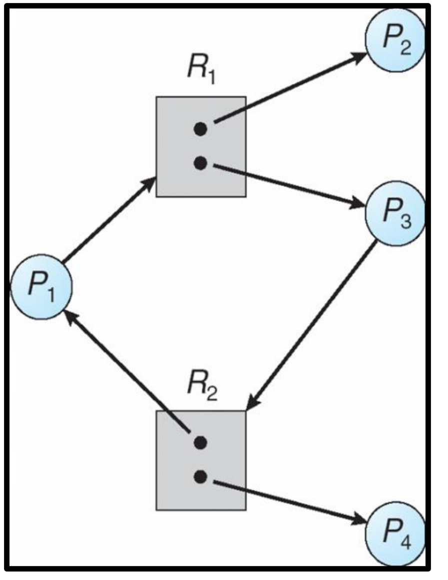




Resource-Allocation Graph Corresponding wait-for graph

Multiple Instances Per Resource

- **n** processes, **m** resources
- **FreeResources**: resource vector (of size m)
  - indicates the number of available resources of each type
  - [R1, R2] = [0,0]
- **Alloc[i]:** process i's allocated resource vector
  - defines the number of resources of each type currently allocated to each process
  - Alloc[1] = [0,1],
  - Alloc[2] = [1, 0], …
- **Request[i]:** process i's requesting resource vector
  - indicates the resources each process requests
  - Request[1] = [1,0],
  - Request[2] = [0,0], …



Detection Algorithm

1. Initialize **Avail** and **Finish** vectors

   Avail = FreeResources;

   For i = 1,2, …, n, Finish[i] = false

2. Find an index i such that

   Finish[i] == false AND Request[i] ≤ Avail

   If no such i exists, go to step 4

3. Avail = Avail + Alloc[i] , Finish[i] = true

   Go to step 2

4. If Finish[i] == false, for some i, 1 ≤ i ≤ n,

   (a) then the system is in deadlock state

- **FreeResources**: resource vector [R1, R2] = [0,0]
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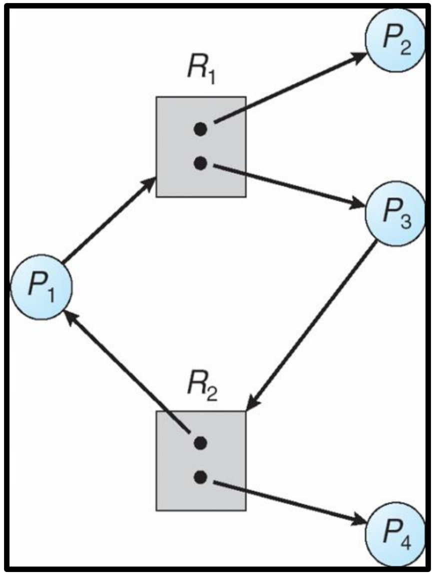

Recovery from Deadlock

- Terminate
  - Preempt the resources
  - Bridge example: throw the car to the river
  - Kill the deadlocked threads and return the resources

- Rollback
  - Return to a known safe state
  - Bridge example: move one car backward
  - Dining philosopher: make one philosopher give up a chopstick

- Not always possible!

Recap: Starvation vs. Deadlock

- Deadlock: circular waiting for resources
  - Example: semaphore A = B = 1

P0	**P1**
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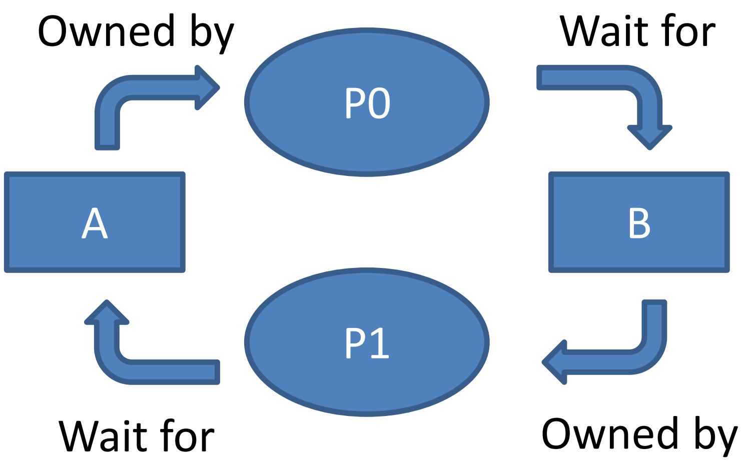
P(B)	P(A)



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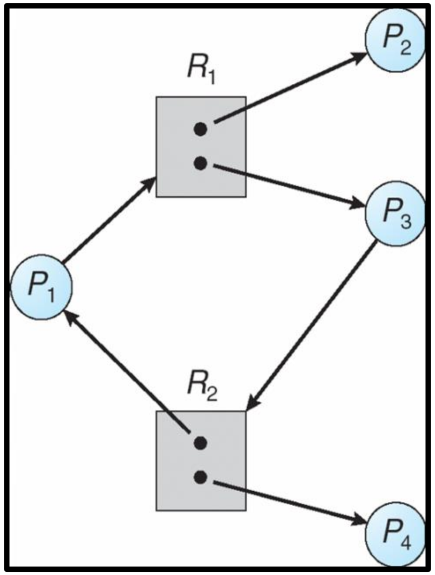

Recap: Recovery from Deadlock

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- Not always possible!

Deadlock Prevention

- Break any of the four deadlock conditions
  - Mutual exclusion
  - No preemption
  - Hold and wait
  - Circular wait

Deadlock Prevention

- Break any of the four deadlock conditions
  - **Mutual exclusion → allow sharing**
    - Well, not all resources are sharable
  - No preemption
  - Hold and wait
  - Circular wait

Deadlock Prevention

- Break any of the four deadlock conditions
  - Mutual exclusion → allow sharing
    - Well, not all resources are sharable
  - **No preemption → allow preemption**
    - This is also quite hard (kill the threads)
  - Hold and wait
  - Circular wait

Deadlock Prevention

- Break any of the four deadlock conditions
  - Mutual exclusion → allow sharing
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  - No preemption → allow preemption
    - This is also quite hard (kill the threads)
  - **Hold and wait → get all resources at once**
    - Dining philosopher: get *both* chopsticks or *none*
  - Circular wait

Deadlock Prevention

- Break any of the four deadlock conditions
  - Mutual exclusion → allow sharing
    - Well, not all resources are sharable
  - No preemption → allow preemption
    - This is also quite hard (kill the threads)
  - Hold and wait → get all resources at once
    - Dining philosopher: get *both* chopsticks or *none*
  - **Circular wait → prevent cycle**
    - Dining philosopher: change the chopstick picking order; **if grabbing a chopstick will form a cycle, prevent it.**

Banker's Algorithm

- General idea
  - Assume that each process's maximum resource demand is known in advance
    - Max[i] : process i's maximum resource demand vector
  - **Pretend** each request is granted, then run the deadlock detection algorithm
  - If a deadlock is detected, the do not grant the request to keep the system in a **safe** state

Banker's Algorithm

1. Initialize **Avail** and **Finish** vectors

   Avail = FreeResources;

   For i = 1,2, …, n, Finish[i] = false

2. Find an index i such that

   Finish[i] == false AND

   Max[i] – Alloc[i] $\leq$ Avail

   If no such i exists, go to step 4

3. Avail = Avail + Alloc[i] , Finish[i] = true

   Go to step 2

4. If Finish[i] == false, for some i, $1 \leq i \leq n$,

   (a) then the system is in deadlock state

   (b) if Finish[i] == false, then P_i is deadlocked

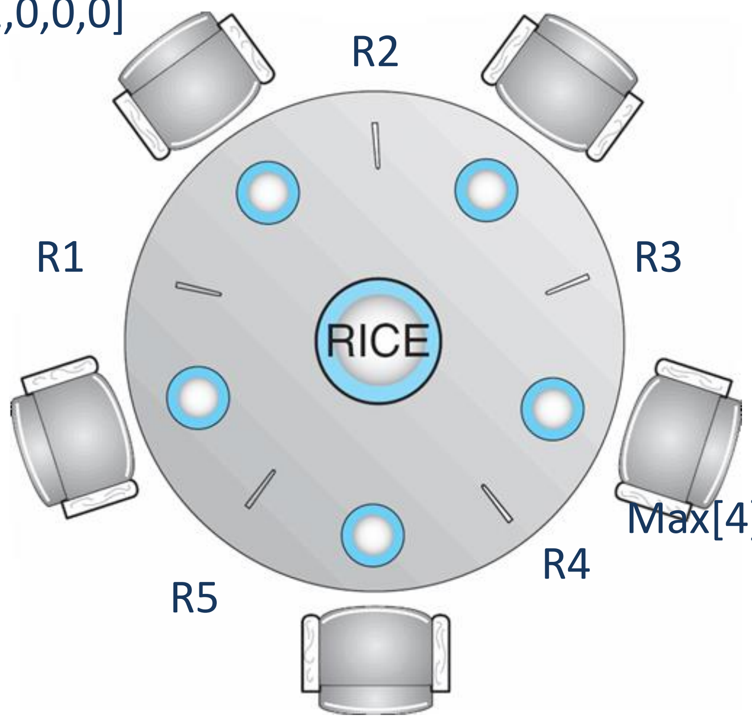
- FreeResources: resource vector [R1, R2] = [0,0]
- Alloc[i]*:* process i's allocated resource vector: Alloc[1] = [0,1], Alloc[2] = [1, 0]
- Request[i]: process i's requesting vector: Request[1] = [1,0] Request[2] = [0,0]
- **Max[i]:** process i's maximum resource demand vector

Example

Free = [1,1,1,1,1]

Max[3] = [0,1,1,0,0]

Max[2] = [1,1,0,0,0]



Max[1] = [1,0,0,0,1]

Max[4] = [0,0,1,1,0]

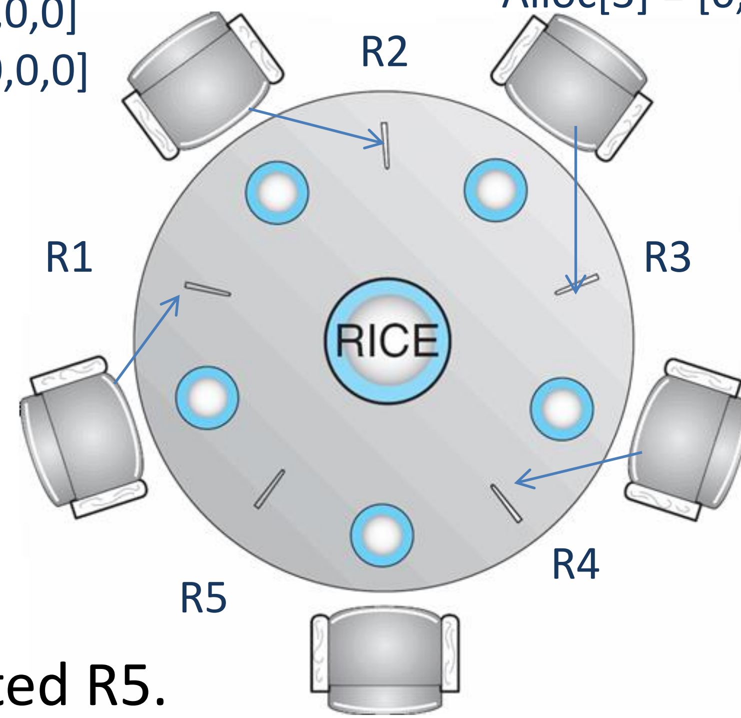
Max[5] = [0,0,0,1,1]

Example

Free = [0,0,0,0,1]
Avail = [0,0,0,0,1]

Max[3] = [0,1,1,0,0]
Alloc[3] = [0,0,1,0,0]

Max[2] = [1,1,0,0,0]
Alloc[2] = [0,1,0,0,0]



Max[1] = [1,0,0,0,1]
Alloc[1]= [1,0,0,0,0]

Max[4] = [0,0,1,1,0]
Alloc[4] = [0,0,0,1,0]

Max[5] = [0,0,0,1,1]
Alloc[5] = [0,0,0,0,0]

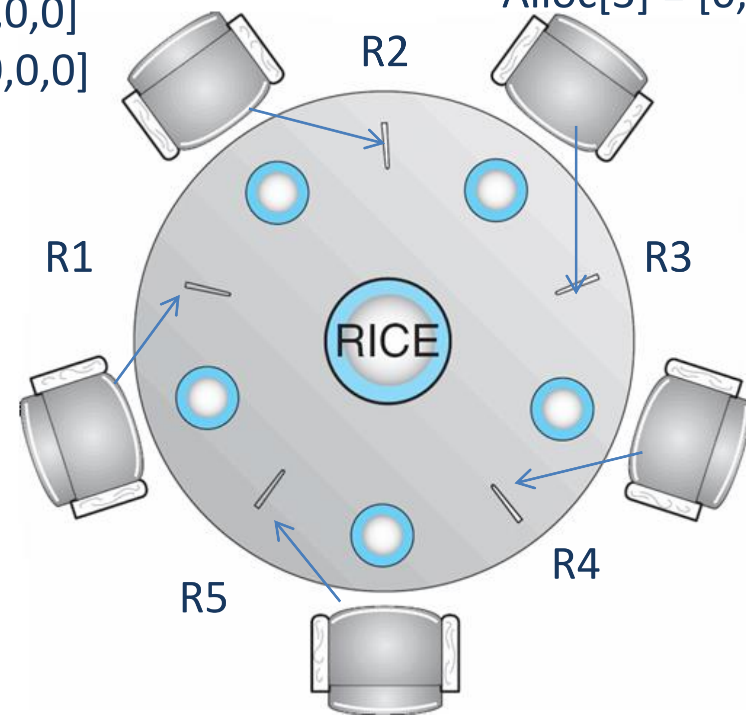
- Philosopher 5 requested R5.
- Safe or Unsafe?

Example

Free = [0,0,0,0,0]
Avail = [0,0,0,0,0]

Max[3] = [0,1,1,0,0]
Alloc[3] = [0,0,1,0,0]

Max[2] = [1,1,0,0,0]
Alloc[2] = [0,1,0,0,0]



Max[1] = [1,0,0,0,1]
Alloc[1]= [1,0,0,0,0]

Max[4] = [0,0,1,1,0]
Alloc[4] = [0,0,0,1,0]

Max[5] = [0,0,0,1,1]
Alloc[5] = [0,0,0,0,1]

2. Find an index i such that
   Finish[i] == false AND
      Max[i] – Alloc[i] $\leq$ Avail
   If no such i exists, go to step 4

Quiz

- Determine whether this state is safe or unsafe.

Total resources: 12

Avail resources: 3

Process	Max	Alloc
P_0	10	4
P_1	3	1
P_2	6	4

10 – 4 <= 8

3 – 1 <= 7

6 – 4 <= 3

Safe

Quiz

- Suppose P0 requested 3 additional resources. Should this request be granted?

Total resources: 12

Avail resources: 0

Process	Max	Alloc
P_0	10	7
P_1	3	1
P_2	6	4

$10 - 7 \not\le 0$

$3 - 1 \not\le 0$

$6 - 4 \not\le 0$

Unsafe

Quiz

- Suppose there are three resource types, which are needed by four processes. Is it safe now?

R1	R2	R3
2	1	2

← Free Resources

	Current Allocation			Max		
Process	R1	R2	R3	R1	R2	R3
P1	0	0	1	0	0	3
P2	2	0	0	2	4	5
P3	0	0	3	6	3	5
P4	2	3	5	4	3	5

← Current and Maximum Allocations

Quiz

- If P2 requests (1, 1, 2), should it be granted?

R1	R2	R3
2	1	2

← Free Resources

	Current Allocation			Max		
Process	R1	R2	R3	R1	R2	R3
P1	0	0	1	0	0	3
P2	2	0	0	3	4	5
P3	0	0	3	6	3	5
P4	2	3	5	4	3	5

← Current and Maximum Allocations

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Quiz

- If P2 requests (1, 1, 2), should it be granted?

R1	R2	R3
1	0	0

← Free Resources

No

	Current Allocation			Max		
Process	R1	R2	R3	R1	R2	R3
P1	0	0	1	0	0	3
P2	3	1	2	3	4	5
P3	0	0	3	6	3	5
P4	2	3	5	4	3	5

← Current and Maximum Allocations

Summary

- Four deadlock conditions:
  - Mutual exclusion
  - No preemption
  - Hold and wait
  - Circular wait
- Detection
- Avoidance
  - Banker's algorithm