Operating Systems (INFR10079)

2023/2024 Semester 2

Deadlocks

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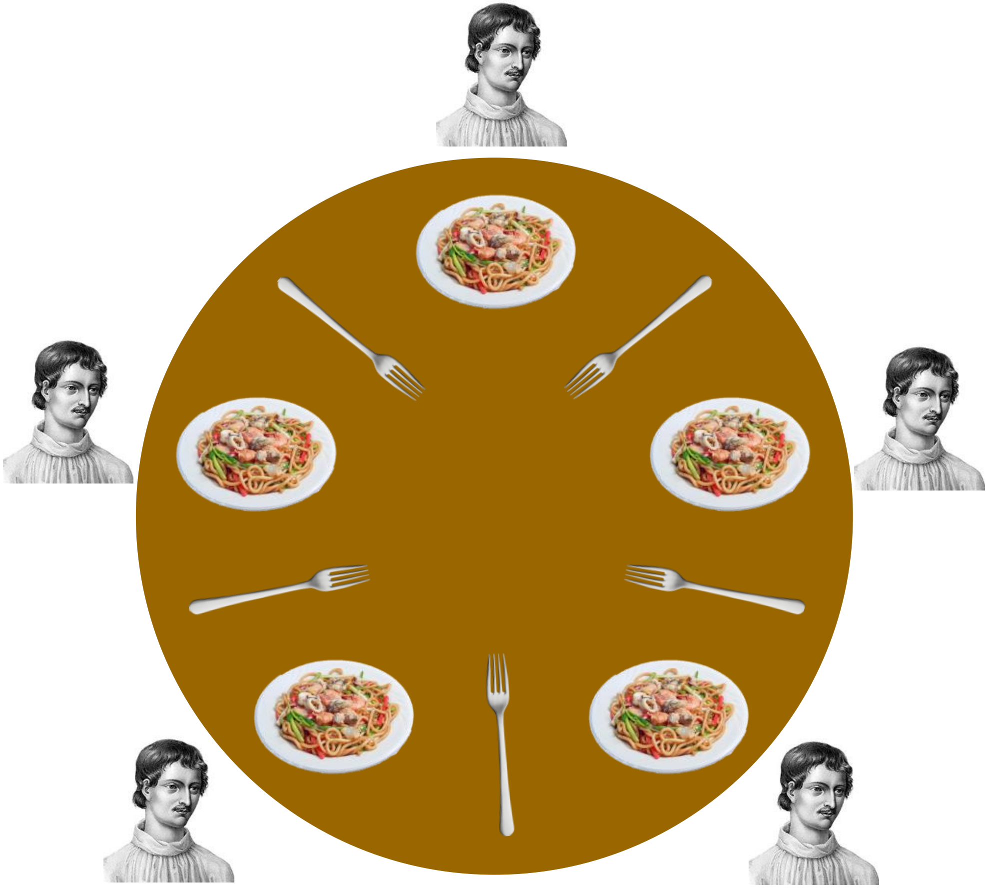
Chapter 8

No one can proceed (by following its own *official* direction)

Dining Philosophers Problem

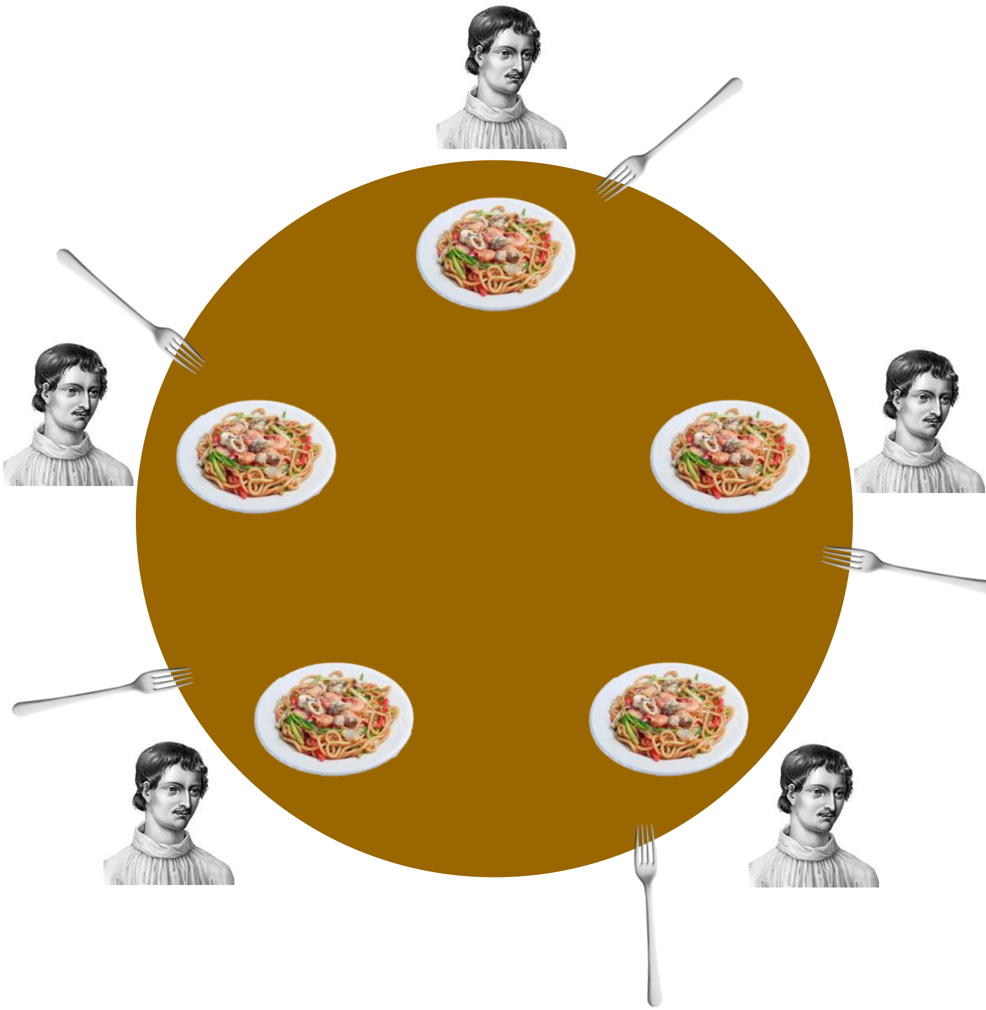
- Dijkstra, 1965
- 5 philosophers, each with
  - A spaghetti dish
  - A fork
- To eat, a philosopher needs **two** forks
  - Spaghetti are too slippery
  - (Yes, we do that in Italy too)
- A philosopher alternates periods of
  - Eating
  - Thinking



Deadlock Problem

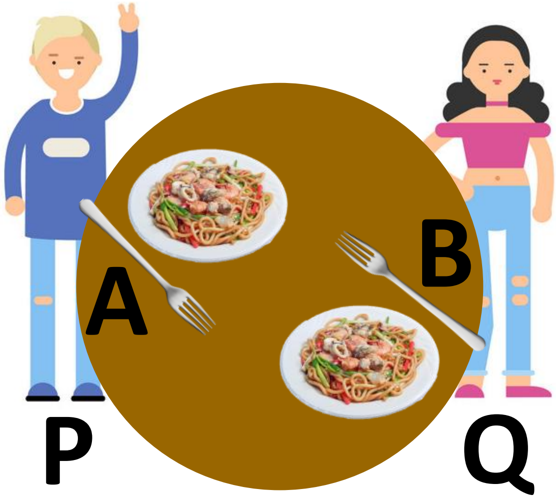
- **When**
- **all grab the fork at their left at the same time**
- **and wait for the one at their right**
  - They will all **indefinitely wait** and no one will eat

- **Cause**
  - Each philosopher needing what another philosopher has
    - Result of sharing resources



Deadlock Example #1

From real-life example to code example



Semaphore muxA = 1 /* protects resource A */

Semaphore muxB = 1 /* protects resource B */

Process P:

```
{
  /* initial compute */
  down(muxA)
  down(muxB)
  /* use both resources */
  up(muxA)
  up(muxB)
}
```

Process Q:

```
{
  /* initial compute */
  down(muxB)
  down(muxA)
  /* use both resources */
  up(muxB)
  up(muxA)
}
```

Possible Deadlock

Deadlock Example #2

From real-life example to code example

Semaphore muxA = 1 /* protects resource A */

Semaphore muxB = 1 /* protects resource B */

Process P: 1

{

/* initial compute */

down(muxA)

4 down(muxB) 2

/* use both resources */

up(muxA)

up(muxB)

}

Process Q:

{

/* initial compute */

down(muxB)

down(muxA) 3

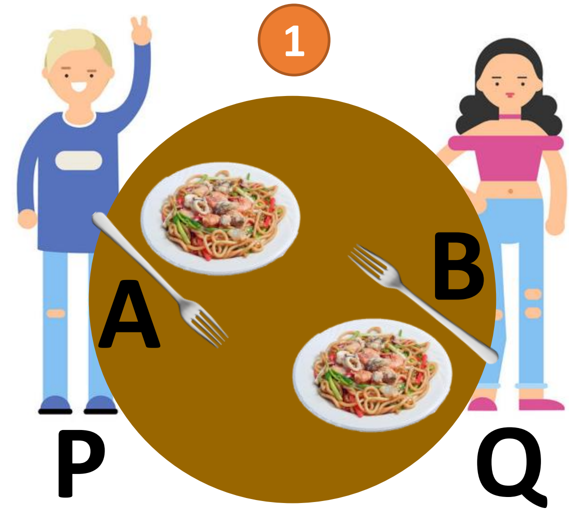
/* use both resources */

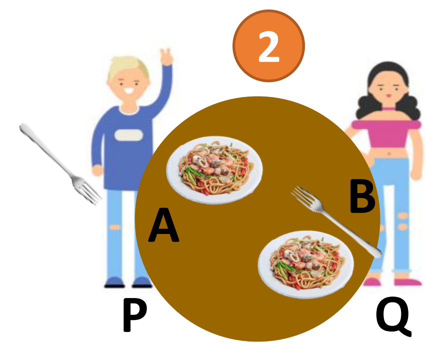
up(muxB)

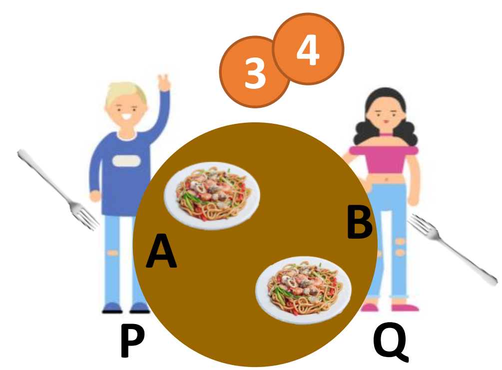
up(muxA)

}

Actual Deadlock







Deadlock Example – Try it out!

```
pthread_mutex_t first_mutex;
pthread_mutex_t second_mutex;
int main() {
  pthread_mutex_init(&first_mutex,NULL);
  pthread_mutex_init(&second_mutex,NULL);
  /** * create thread one and thread two */
  /** * wait threads to finish */
  return 0;
}
/* thread one runs in this function */
void *do_work_one(void *param)
{
   pthread_mutex_lock(&first_mutex);
   pthread_mutex_lock(&second_mutex);
   /** * Do some work */
   pthread_mutex_unlock(&second_mutex);
   pthread_mutex_unlock(&first_mutex);
   pthread_exit(0);
}
/* thread two runs in this function */
void *do_work_two(void *param)
{
   pthread_mutex_lock(&second_mutex);
   pthread_mutex_lock(&first_mutex);
   /** * Do some work */
   pthread_mutex_unlock(&first_mutex);
   pthread_mutex_unlock(&second_mutex);
   pthread_exit(0);
}
```

- Complete the program
  - Add `pthread_create`, and `pthread_join`
  - Add `printf` to track program progresses
- Compile the program
  - Don't forget `-pthread`
- Run the program
  - How many times should run it before a deadlock?

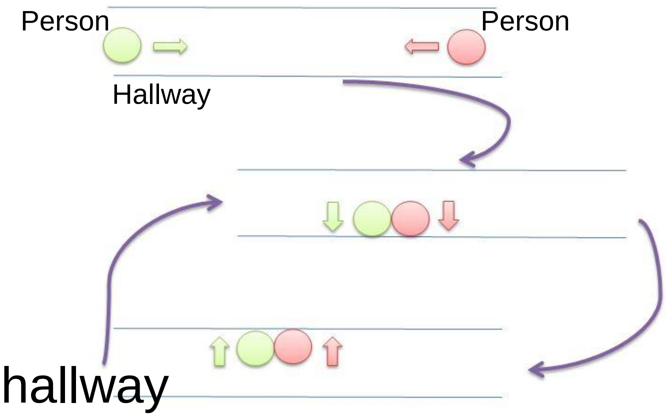
Deadlock

- In a **multiprogramming** environment
  - Threads or processes compete for a finite number of resources
  - Each thread or process requests resources
  - If resources are not available, the thread or process waits
  - Waiting thread or process **never runs again** because the requested resource(s) is(are) held by other waiting threads or processes

- **Liveness failure**

- Deadlock **Definition**
  - A situation in which every process/thread in a set of processes/threads
  - **is waiting for an event** that can be **caused only by another process/thread in the set**

Livelock



- Example
  - **Two people** (red/green) attempt to pass in a hallway
  - One moves to his right, the other to her left
    - still obstructing each other's progress
  - Then he moves to his left, and she moves to her right, and so forth
- They aren't blocked, but they aren't making any progress

- **Liveness failure**, similar to deadlock
  - Both prevent two or more threads/processes from proceeding
  - Threads/processes are unable to proceed **for different reasons**

- **Deadlock**
  - Occurs when every thread/process in a set **is blocked waiting** for an event that can be caused only by another thread/process in the set
- **Livelock**
  - Occurs when a thread/process **continuously attempts** an action that fails

The next slides focus on deadlock

Necessary Conditions for **Deadlock**

A. **Mutual exclusion**
   - Each resource is either currently assigned to exactly **one** process/thread or is available

B. **Hold and wait**
   - Processes/threads currently holding resources that were granted earlier can request new resources

C. **No preemption**
   - Resources previously granted cannot be forcibly taken away from a process/thread
     - They must be explicitly released by the process/thread holding them

D. **Circular wait**
   - There must be a circular list of two or more processes/thread
     - Each waiting for a resource held by the next member of the chain

All conditions must hold for a deadlock to occur

System Model
(Resources and Processes)

*A system consists of a **finite number of resources**, partitioned into several types/classes, to be **distributed among a number of competing threads/processes***

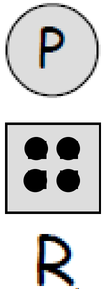
- Resource types/classes (***m***)
  - $R_1, R_2, \dots, R_m$
  - E.g., printers, disks, etc.
- Each resource type R_i has E_i instances
  - E.g., 3 printers, 5 disks, etc.
- Assume serially reusable resources
  - request -> use -> release

- Processes (***n***)
  - $P_1, P_2, \dots, P_n$
  - Instead of processes a model with **threads** can be developed

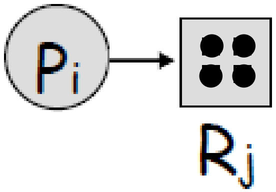
Resource-allocation Graph

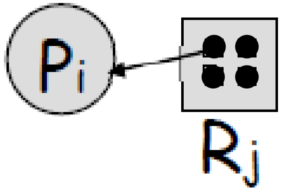
- A way to visualize **CURRENT STATE** of threads/processes
  - Like a snapshot
- A set of vertices ***V*** and a set of edges ***E***

- ***V*** is partitioned into two types
  - **Process** vertices $\boldsymbol{P = \{P_1, P_2, \ldots, Pn\}}$, the set of processes
  - **Resource** vertices $\boldsymbol{R = \{R_1, R_2, \ldots, R_m\}}$, the set of resource types
    - **Not resources!**

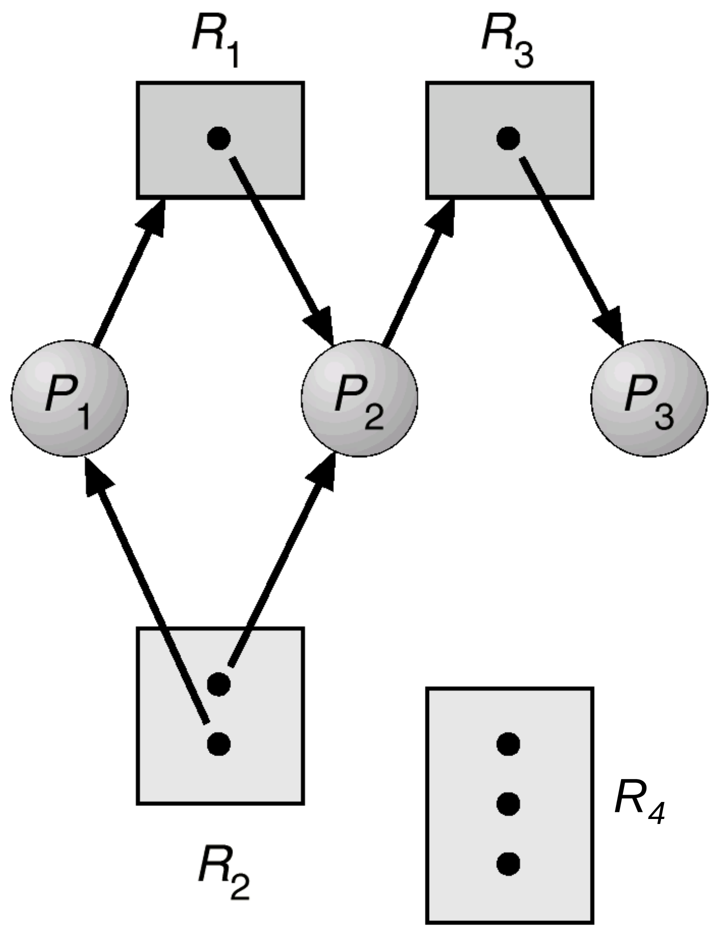


- ***E*** is partitioned into two types
  - **Request** edge – directed edge $\boldsymbol{P_i \text{-}> R_j}$
    - **The process is blocked waiting for that resource**
  - **Assignment** edge – directed edge $\boldsymbol{R_j \text{-}> P_i}$
    - **The process owns the resource**



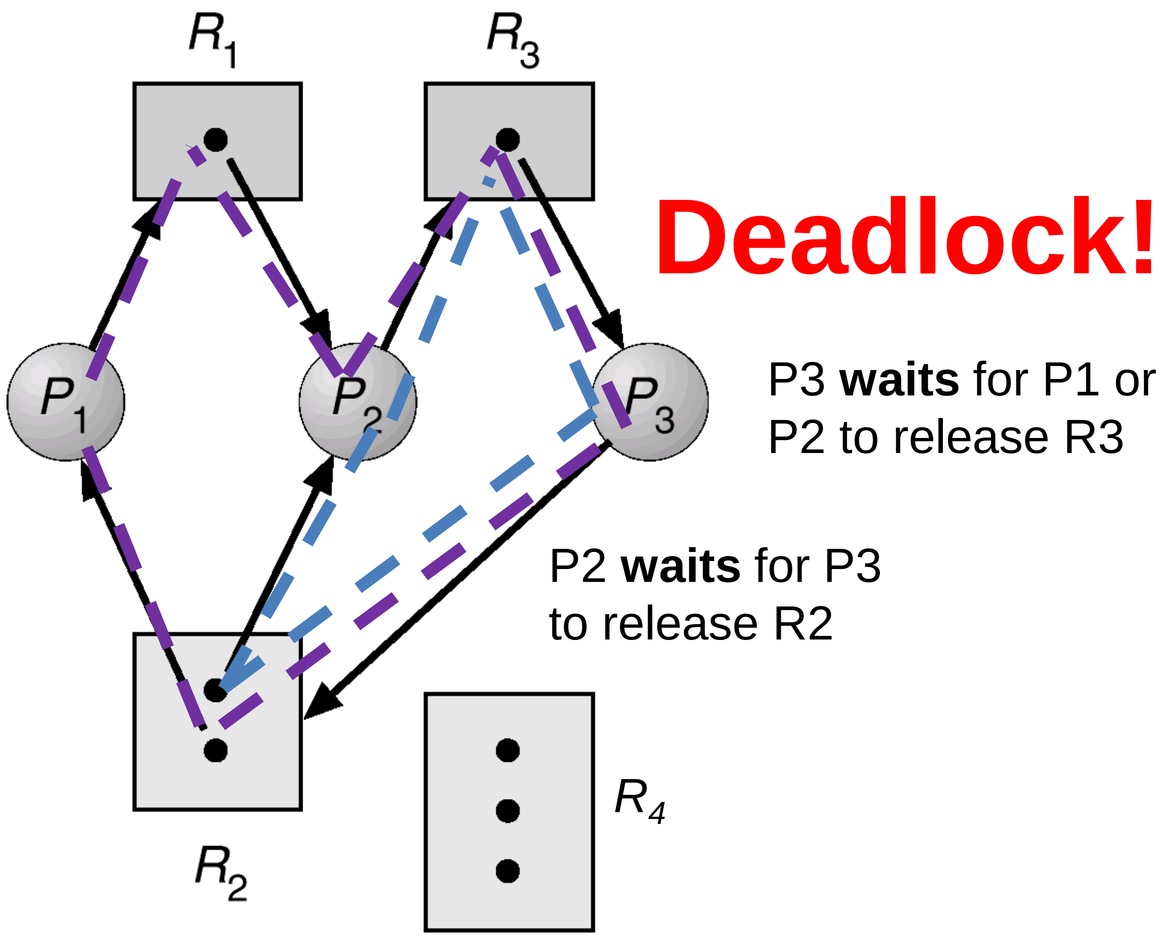


Resource Allocation Graph with No Cycle **and No Deadlock**



Graph contains **no cycles** → **No** thread/process is **deadlocked**

Resource Allocation Graph with Cycles **and Deadlock**



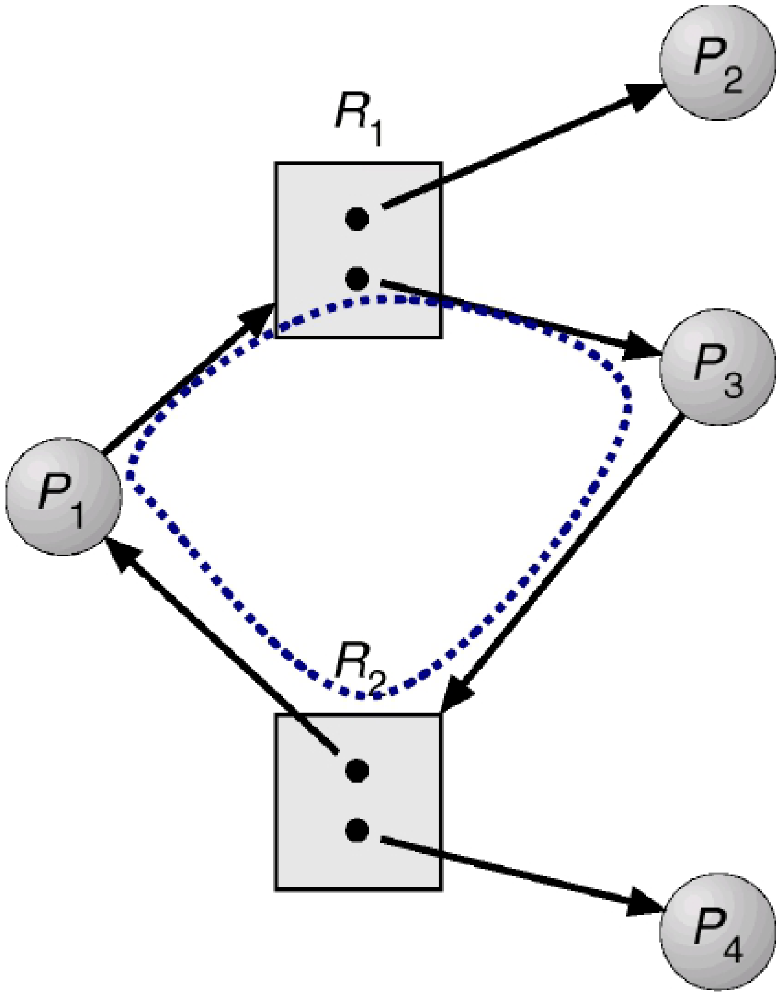
P1 **waits** for P2 to release R1

P3 **waits** for P1 or P2 to release R3

P2 **waits** for P3 to release R2

If the graph **contains a cycle**, then a deadlock **may exist**

Resource Allocation Graph with Cycle **and No Deadlock**



A cycle **is not sufficient** to imply a deadlock

Notes

- If each resource type has **exactly one instance**
  - Then a cycle implies that a **deadlock has occurred**
- If the cycle involves only **a set of resource types,** each of which has **only a single instance**
  - Then a **deadlock has occurred**
- Each thread involved in the cycle is deadlocked
  - A cycle in the graph is both **a necessary and a sufficient condition**

- If each resource type has **several instances**
  - then a cycle doesn’t necessarily imply that a deadlock has occurred
  - a cycle in the graph **is a necessary but not a sufficient condition** for the existence of deadlock

HOW TO DEAL WITH DEADLOCKS?

Handling Deadlocks

- Ensure deadlock **never** occurs
  - **Prevention** (development time)
    - Negate one of the four necessary conditions
  - **Avoidance** (runtime)
    - Each resource request is analyzed and denied if may deadlock
- Allow deadlock to **happen**
  - **Detection and recovery**
    - System enters a deadlocked state, detect it, and recover
    - **Example:** databases
  - **Do nothing** (Ostrich algorithm)***
    - Ignore the problem and pretend deadlocks never occur
    - **Example:** most operating systems, including Linux and Windows

Deadlock **Prevention**

- Principle (Havender, 1968)
  - Ensure that at least one of the **necessary conditions** cannot hold
    - Mutual exclusion
    - Hold and wait
    - No preemption
    - Circular wait
  - Hence, deadlocks will be structurally impossible

- **Requires to change the way software is written**
  - Thus, at development time

Attacking the **Mutual Exclusion** Condition

- **Idea**
  - Avoid assigning a resource unless absolutely necessary
  - Try to make sure that as few processes as possible may actually claim the resource
- Practically
  - For read, don’t assign resources to a single process
    - Make data read only
  - For write, use a mediator which serializes the write
    - Spooler example, the mediator is the spooler daemon
- **Problem**
  - Processes may deadlock filling up the mediator

Attacking the **Hold and Wait** Condition

- **Idea**
  - Prevent processes that hold resources from waiting for more resources
- Practically
  - Require all processes to request all their resources before “starting execution”
  - If everything is available, the process will be allocated whatever it needs and can run to completion
  - If one or more resources are busy, nothing will be allocated, and the process will just wait
    - And then reallocate everything again
- **Problem**
  - Processes don’t know about all needed resources

Attacking the **No Preemption** Condition

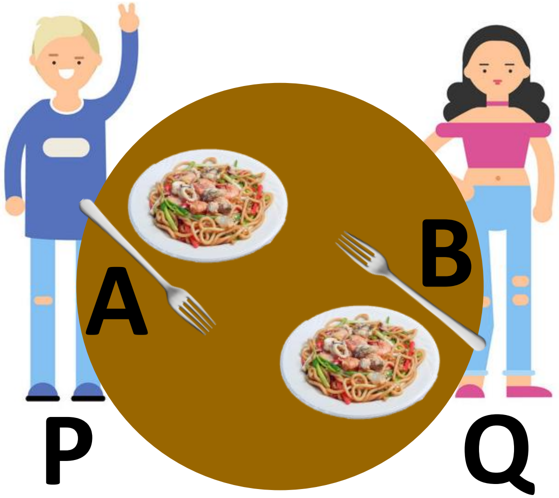
- **Idea**
  - If a process is holding some resources
  - and request another resource that is not available,
  - then all resources the process is currently holding are preempted (released)
- Practically
  - Applied to resources whose state can be saved and restored later
    - CPU registers, memory space, etc.
- **Problem**
  - Not all resources can be virtualized

Attacking the **Circular Wait** Condition

- **Idea**
  - All requests of resources must be made in numerical order by processes
- Practically
  - See Figure
- **Problem**
  - May be impossible to find an ordering to satisfy everyone

Deadlock Example

How to solve this with **Deadlock Prevention**



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  down(muxB)
  /* use both resources */
  up(muxB)
  up(muxA)
}
```

Deadlock-free code!

Deadlock Avoidance

- **The OS/runtime**
- Be given **additional information** in advance
  - What resources a thread/process will **request and use** during lifetime
  - Complete **sequence of requests and releases** of each thread/process
- **Decides for each request** if a thread/process waits, considering the **resource-allocation state**
  - **Currently available** resources
  - **Currently allocated** resources to each thread/process
  - **Future requests** and releases of each thread/process

- Algorithm dynamically examines resource-allocation state
  - For **circular-wait condition** existence

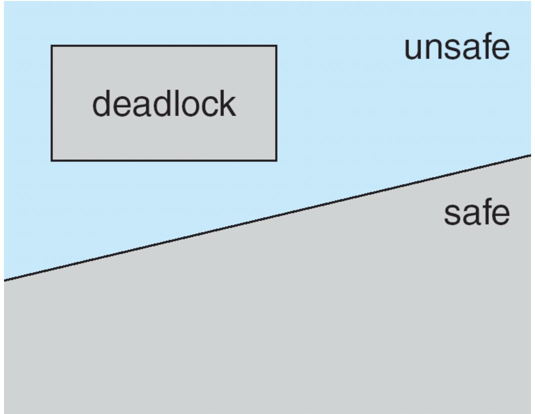
Safe State

- If the system **can allocate resources** to each thread/process (up to its maximum) **in some order** and still **avoid deadlocks**

- A system is in a safe state only if there exists a **safe sequence**
  - A sequence $<P_1, P_2, \ldots, P_n>$ of **ALL the processes in the systems**
  - For each P_i, the resources that P_i can still request can be satisfied by
    - Currently **available resources** plus
    - **Resources held** by all the P_j, with $j < i$
  - In this situation, if P_i resource needs **are not immediately available**
    - P_i can wait until all P_j have finished
    - P_i can obtain needed resources, execute, return allocated resources, and terminate
    - When P_i terminates, P_{i+1} can obtain its needed resources, and so on

Safe, Unsafe, Deadlock States

- A **safe state** is not a **deadlocked state**
- A **deadlocked state** is an **unsafe state**
  - Not all **unsafe states** are **deadlocks**
- An **unsafe state** may lead to a **deadlock**



- In a **safe state**
  - OS/runtime **can avoid unsafe (and deadlocked) states**
- In an **unsafe state**
  - OS/runtime **cannot prevent** threads from requesting resources in such a way that a **deadlock occurs**

- Deadlock avoidance **algorithms**
  - **One instance** of each resource type: graph algorithm + claim edge
  - **Multiple instances** of each resource type: Banker algorithm

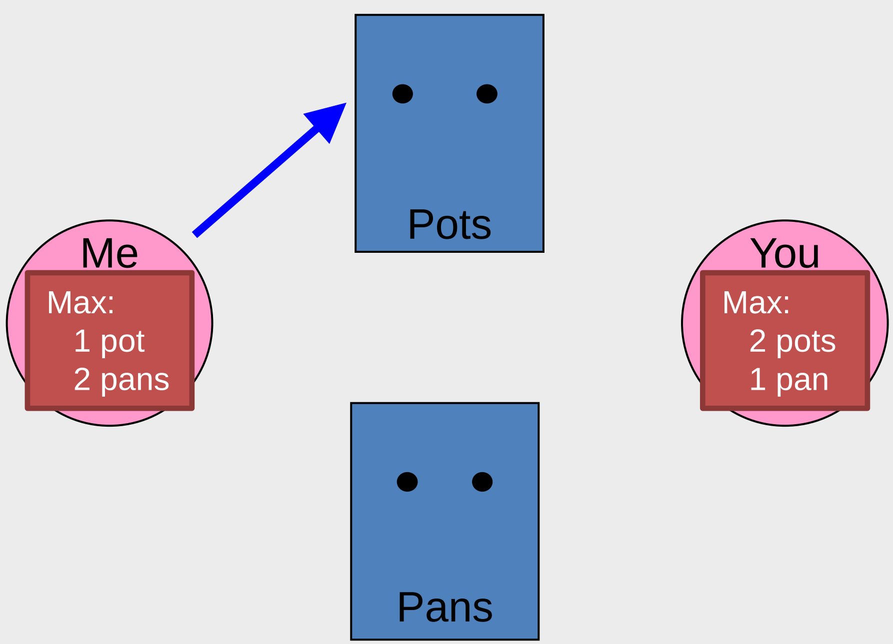
Banker's Algorithm

- Algorithm could be used in a **banking system**
  - To ensure the bank never allocated its available cash in such a way that it could no longer satisfy the needs of all its customers

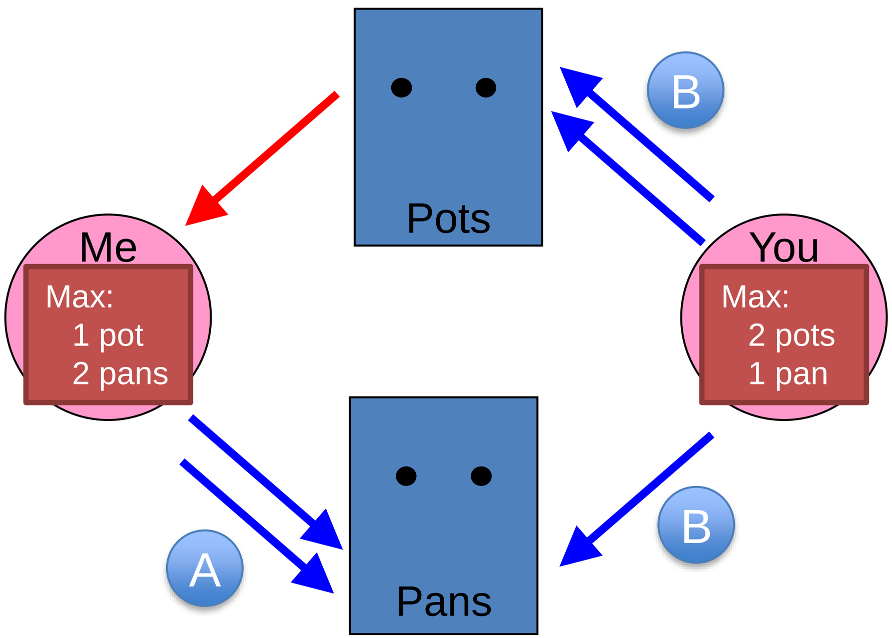
- Background
  - Set of **controlled resources** is known to the system
  - **Number of units** of each resource is known to the system
  - Each application declares **maximum possible requirement** of each resource type
- When an **application requests** a set of resource
  - System determine whether the allocation of these resources will **leave the system in a safe state**
    - YES, the resources are allocated
    - NO, must wait until some other releases enough resources

Banker's Example
Request 1

- I request a pot



- Suppose we allocate, then everyone requests its max

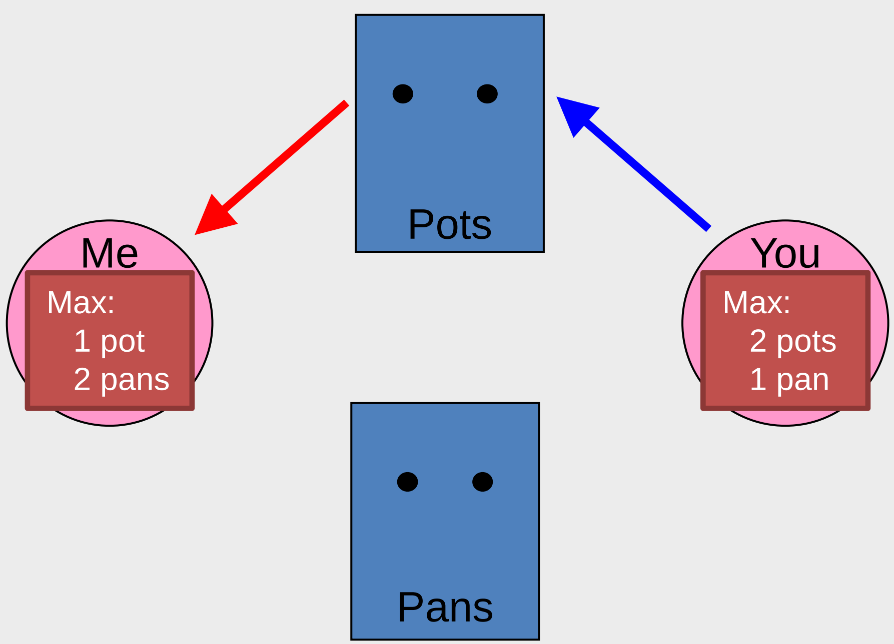


First, I acquire all my resources and then you do the same

Safe state

Banker's Example
Request 2

- You request a pot



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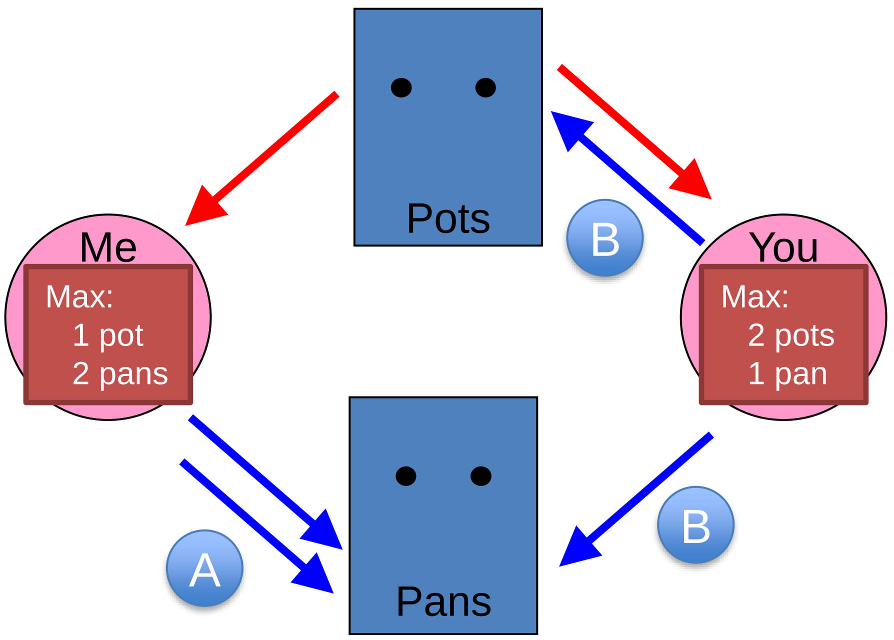
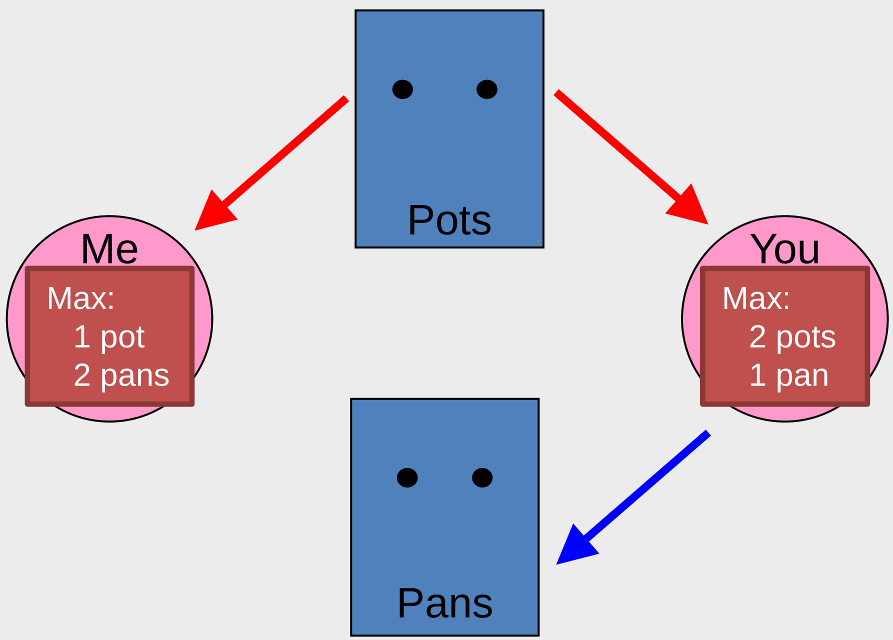


First, I acquire all my resources and then you do the same

Safe state

Banker's Example
Request 3a

- You request a pan



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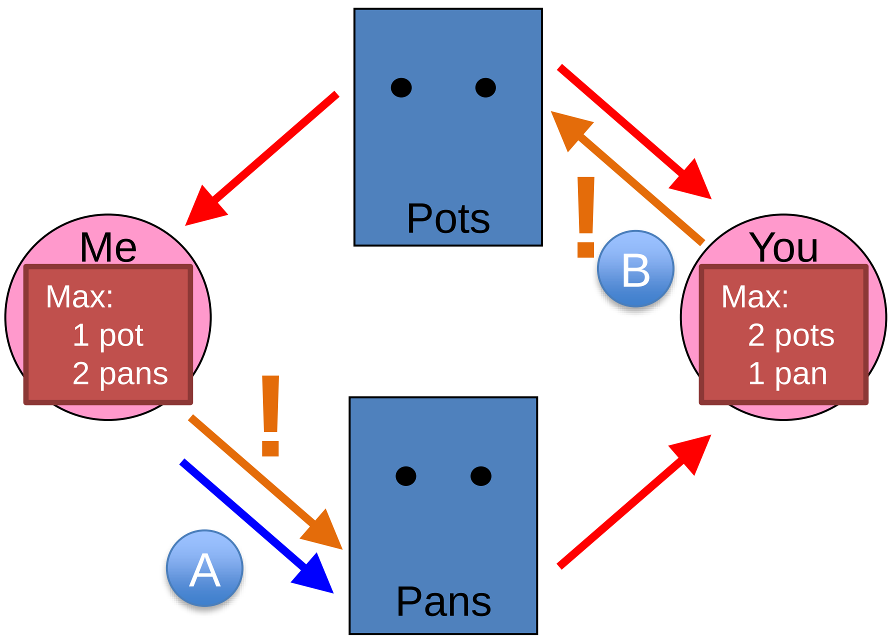
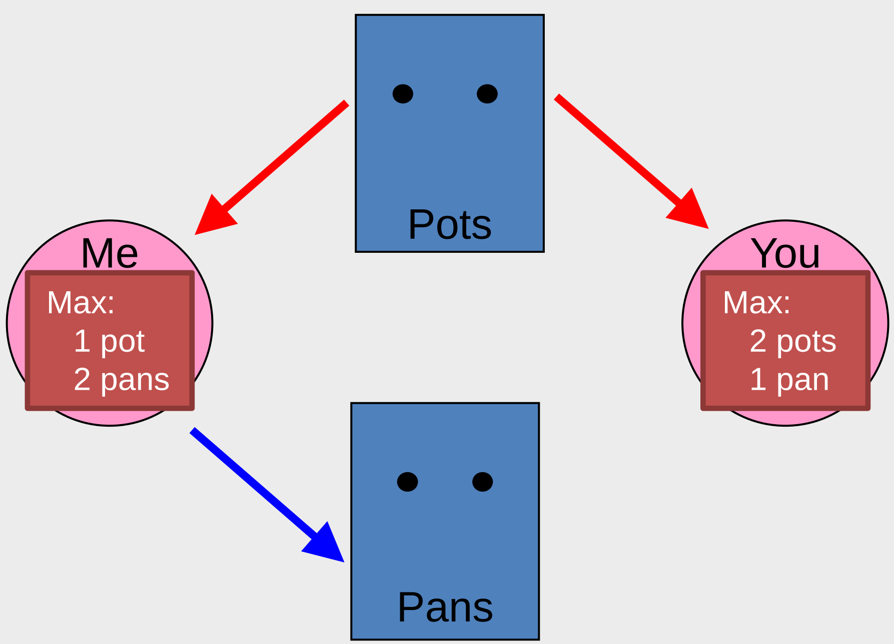


First, I acquire all my resources and then you do the same (A) – not possible!
First, you acquire all your resources and then I do the same (B) – not possible!

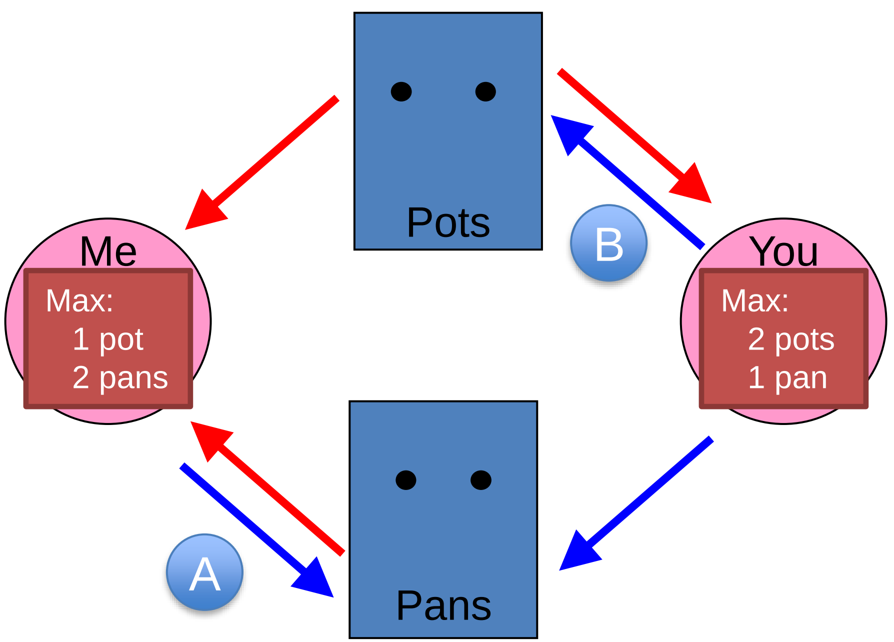
UNSAFE state

Banker's Example
Request 3b

- I request a pan



- Suppose we allocate, then everyone requests its max



First, I acquire all my resources and then you do the same

Safe state

Banker's Algorithm **Implementation** #1

- Data Structures
  - *n* = number of threads/processes
  - *m* = number of resource types
  - **Available** – vector of length *m*
    - Number of available resources of each type
  - **Max** – matrix *n* x *m*
    - Maximum demand of each thread/process
  - **Allocation** – matrix *n* x *m*
    - Number of resources of each type currently allocated to each thread or process
  - **Need** – matrix *n* x *m*
    - Remaining resource need of each thread/processes
  - **Need** [i,j] = **Max** [i,j] – **Allocation** [i,j]
    - Either Need or Max are used

Banker's Algorithm **Implementation** #2

- **Safety Algorithm**

1. Let ***Work*** and ***Finish*** be vectors of length *m* and *n*, respectively. Initialize:

   Work = Available

   ***Finish* [*i*] = *false* for *i* = 0, 1, …, *n*- 1**

2. Find an ***i*** such that both:

   (a) ***Finish* [*i*] = *false***

   (b) $\boldsymbol{Need_i \leq Work}$

   If no such ***i*** exists, go to step 4

3. $\boldsymbol{Work = Work + Allocation_i}$

   Finish*[*i*] = *true

   go to step 2

4. If ***Finish* [*i*] == *true*** for all ***i***, then the system is in a safe

Banker's Algorithm **Implementation** #3

- **Resource-Request Algorithm for Process$_i$**

Request$_i$ = request vector for process ***P$_i$***. If ***Request$_i$* [*j*] = *k*** then process ***P$_i$*** wants ***k*** instances of resource type ***R$_j$***

1. If ***Request$_i$*** $\leq$ ***Need$_i$*** go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim
2. If ***Request$_i$*** $\leq$ ***Available***, go to step 3. Otherwise ***P$_i$*** must wait, since resources are not available
3. Pretend to allocate requested resources to ***P$_i$*** by modifying the state as follows:

$$\boldsymbol{Available = Available - Request_i;}$$
$$\boldsymbol{Allocation_i = Allocation_i + Request_i;}$$
$$\boldsymbol{Need_i = Need_i - Request_i;}$$

- If safe $\Rightarrow$ the resources are allocated to ***P$_i$***
- If unsafe $\Rightarrow$ ***P$_i$*** must wait, and the old resource-allocation state is restored

Banker's Algorithm **Example**

- 5 processes P_0 through P_4;
  3 resource types:
  A (10 instances), *B* (5instances), and *C* (7 instances)
- Snapshot at time T_0:

	Allocation	*Max*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	7 5 3	3 3 2
P_1	2 0 0	3 2 2	
P_2	3 0 2	9 0 2	
P_3	2 1 1	2 2 2	
P_4	0 0 2	4 3 3	

	Need
	A B C
P_0	7 4 3
P_1	1 2 2
P_2	6 0 0
P_3	0 1 1
P_4	4 3 1

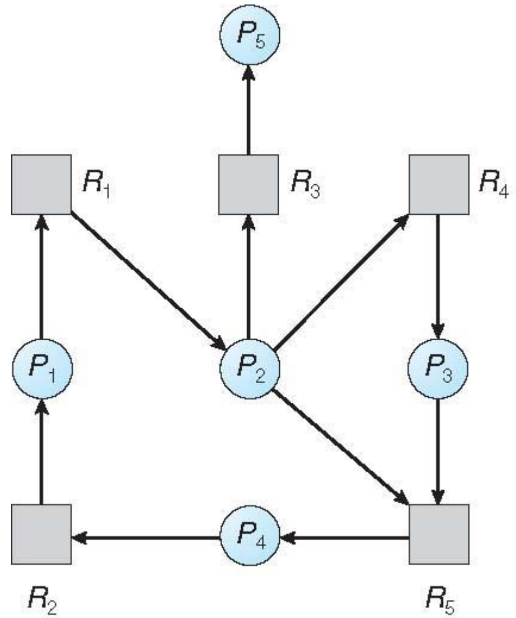
Full example Section 8.6.3.3

Deadlock Detection and Recovery

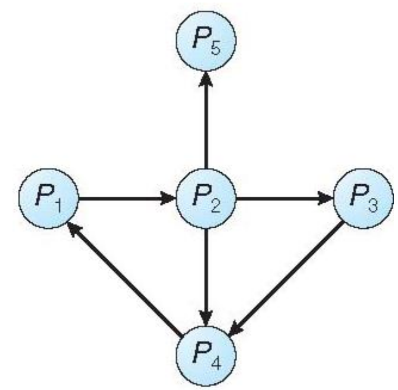
- Allow system to **enter a deadlock state**
- **Detection**
  - Algorithm that examines the state of the system to determine whether a deadlock has occurred
    - Wait-for graph (single instance)
    - Variation of the Banker Algorithm (multiple instances)
- **Recovery scheme**
  - Algorithm to recover from the deadlock

Detection
Single Instance of Each Resource Type

- Maintain **wait-for** graph
  - Nodes are processes
  - $P_i \rightarrow P_j$ if P_i is waiting for P_j
- **Periodically searches** for cycles in the graph
  - A cycle implies a deadlock
- An algorithm to **perform search**
  - Requires an order of n^2 operations
    - n is the number of vertices in the graph
- **Doesn't apply** for multiple instances of each resource type
  - Variation of the banker algorithm



Resource allocation graph



Wait-for graph

Recovery from Deadlock

- **Process/Thread Termination**
  - Abort **all** deadlocked processes
  - Abort **one** process at a time until the deadlock cycle is eliminated
    - What process to select?
- May leave resources in an **incorrect state**

- **Resource Preemption**
- Successively preempt resources from thread/processes and give them to others until deadlock cycle is broken
  1. **Selecting a victim** – resource and process to preempt
  2. **Rollback** – return to some safe state, restart process for that state
  3. **Starvation** – avoid same process/thread as victim

- Instead of recovering the **operator can be informed**