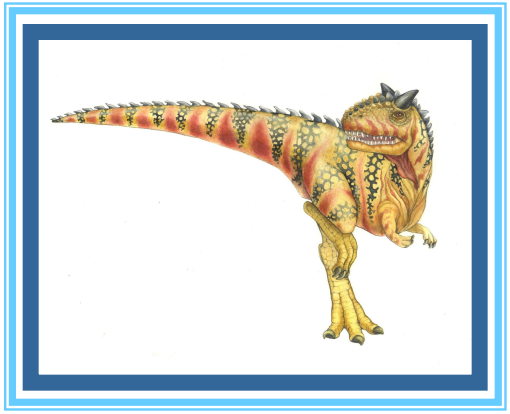
Chapter 8: Deadlocks



Outline

- System Model
- Deadlock Characterization
- Methods for Handling Deadlocks
- Deadlock Prevention
- Deadlock Avoidance
- Deadlock Detection
- Recovery from Deadlock

Chapter Objectives

- Illustrate how deadlock can occur when mutex locks are used
- Define the four necessary conditions that characterize deadlock
- Identify a deadlock situation in a resource allocation graph
- Evaluate the four different approaches for preventing deadlocks
- Apply the banker's algorithm for deadlock avoidance
- Apply the deadlock detection algorithm
- Evaluate approaches for recovering from deadlock

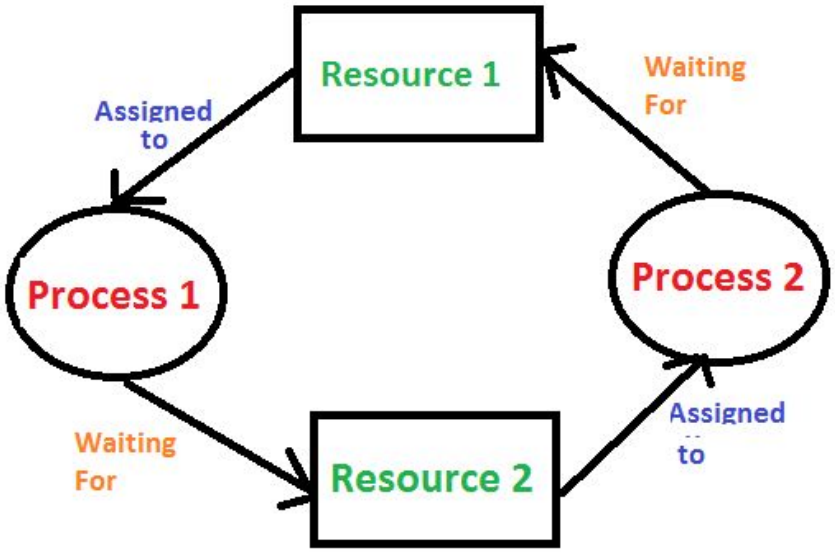
System Model

- System consists of resources
- Resource types $R_1, R_2, \ldots, R_m$
  - *CPU cycles, memory space, I/O devices*
- Each resource type R_i has W_i instances.
  - Single instances: Monitor
  - Multiple instances: Register
- Each process utilizes a resource as follows:
  - Requests a resource
  - Use the resource
  - Releases the resource

Deadlock

- A deadlock is a situation where a set of processes are blocked because each process is holding a resource and waiting for another resource acquired by some other process.

A similar situation occurs in operating systems when there are two or more processes that hold some resources and wait for resources held by other(s). For example, in the below diagram, Process 1 is holding Resource 1 and waiting for resource 2 which is acquired by process 2, and process 2 is waiting for resource 1.



Deadlock with Semaphores

- Data:
  - A semaphore s_1 initialized to 1
  - A semaphore s_2 initialized to 1
- Two threads T_1 and T_2
- T_1:

```
wait(s1)
wait(s2)
```

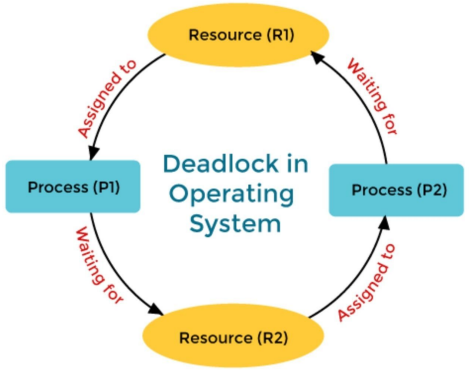
- T_2:

```
wait(s2)
wait(s1)
```

Deadlock Characterization

Deadlock can arise if four conditions hold simultaneously.

- **Mutual exclusion:** only one thread at a time can use a resource
- **Hold and wait:** a thread holding at least one resource is waiting to acquire additional resources held by other threads
- **No preemption:** a resource can be released only voluntarily by the thread holding it, after that thread has completed its task
- **Circular wait:** there exists a set $\{T_0, T_1, \ldots, T_n\}$ of waiting threads such that T_0 is waiting for a resource that is held by T_1, T_1 is waiting for a resource that is held by T_2, …, T_{n-1} is waiting for a resource that is held by T_n, and T_n is waiting for a resource that is held by T_0.



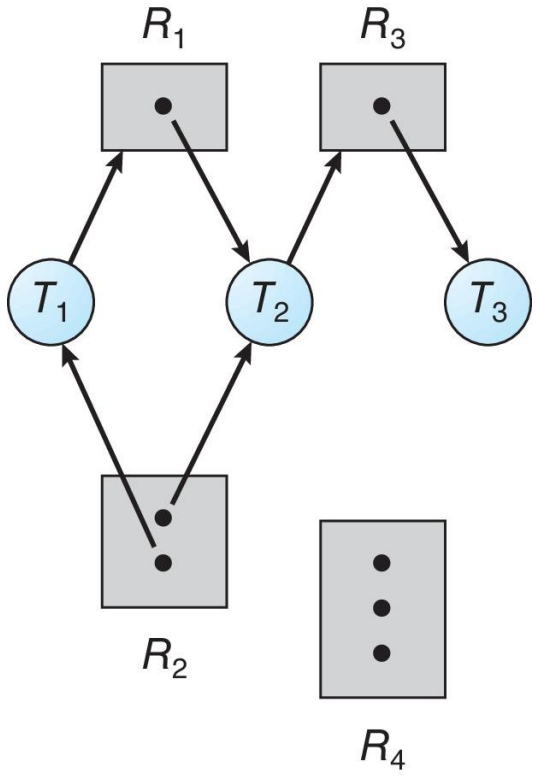
Resource-Allocation Graph

A set of vertices V and a set of edges E.

- V is partitioned into two types:
  - $T = \{T_1, T_2, \ldots, T_n\}$, the set consisting of all the threads 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 $T_i \rightarrow R_j$
- **assignment edge** – directed edge $R_j \rightarrow T_i$

Resource Allocation Graph Example

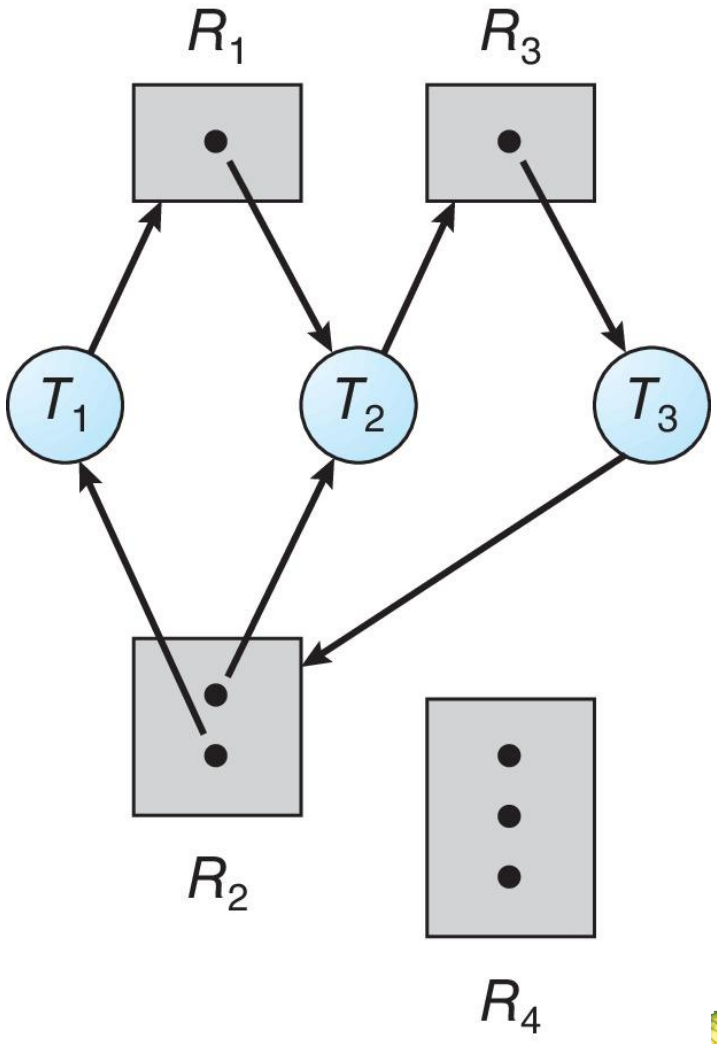
- One instance of R_1
- Two instances of R_2
- One instance of R_3
- Three instance of R_4
- T_1 holds one instance of R_2 and is waiting for an instance of R_1
- T_2 holds one instance of R_1, one instance of R_2, and is waiting for an instance of R_3
- T_3 is holds one instance of R_3



Resource Allocation Graph with a Deadlock

T1□R1 ;R2□T1
T2□R3; R1□T2;R2□T2
T3□R2;R3□T3

Does it have circular wait?
Hold and wait?
Preemption?



Process	Allocation R1	R2	R3	Request R1	R2	R3
T1	0	1	0	1	0	0
T2	1	1	0	0	0	1
T3	0	0	1	0	1	0

Availability (0 0 0)
Does this availability fullfill any process's requirement?
Deadlock.

Graph with a Cycle But no Deadlock

Process	Allocation R1	R2	Request R1	R2
T1	0	1	1	0
T2	1	0	0	0
T3	1	0	0	1
T4	0	1	0	0

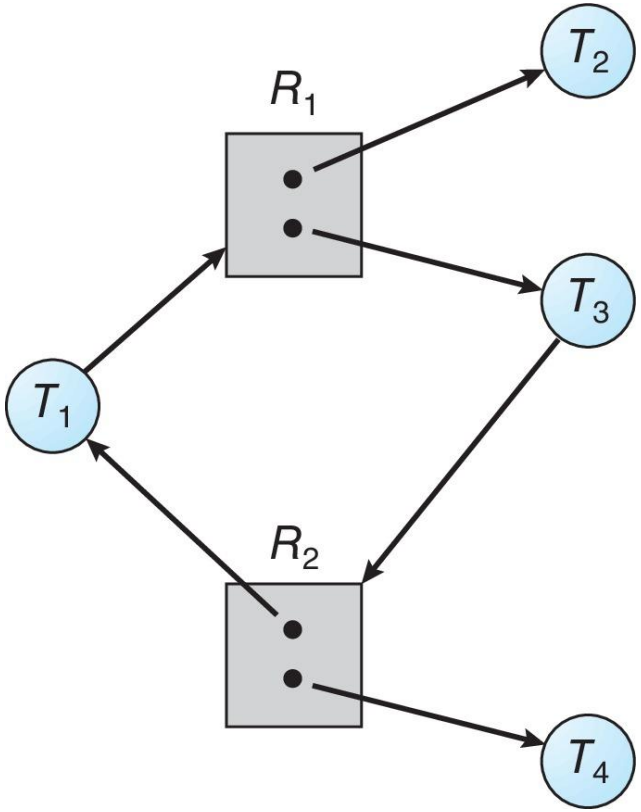
Initially Availability (0 0)

Step 1 : T4 releases R2
Availability(0 1)

Step 2 :T3 releases R1 and R2
previous 0 1
release 1 0

Availability(1 1)

Then?



Basic Facts

- If graph contains no cycles ⇒ **no deadlock**
- If graph contains a cycle ⇒
  - if only **one instance** per resource type, then deadlock
  - if **several instances** per resource type, possibility of deadlock

Methods for Handling Deadlocks

- Ensure that the system will **never** enter a deadlock state:
  - **Deadlock prevention** : The idea is to not let the system into a deadlock state. This system will make sure that mentioned four conditions will not arise.
  - **Deadlock avoidance** : We need to ensure that all information about resources that the process will need is known to us before the execution of the process. Ex Banker's Algorithm
  - **Deadlock Ignorance** : If a deadlock is very rare, then let it happen and reboot the system. This is the approach that both Windows and UNIX take. we use the ostrich algorithm for deadlock ignorance.
  - **Deadlock detection and recovery**

Safe State: A safe state can be defined as a state in which there is no deadlock. It is achievable if:

- If a process needs an unavailable resource, it may wait until the same has been released by a process to which it has already been allocated. if such a sequence does not exist, it is an unsafe state.
- All the requested resources are allocated to the process.

Deadlock Prevention

Invalidate one of the four necessary conditions for deadlock:

- **Mutual Exclusion** – not required for sharable resources (e.g., read-only files); must hold for non-sharable resources.
- **Hold and Wait** – must guarantee that whenever a thread requests a resource, it does not hold any other resources
  - Require threads to request and be allocated all its resources before it begins execution or allow thread to request resources only when the thread has none allocated to it.
  - Low resource utilization; starvation possible

Deadlock Prevention (Cont.)

- **No Preemption**:
  - If a process that is holding some resources requests another resource that cannot be immediately allocated to it, then all resources currently being held are released
  - Preempted resources are added to the list of resources for which the thread is waiting
  - Thread will be restarted only when it can regain its old resources, as well as the new ones that it is requesting
- **Circular Wait:**
  - Impose a total ordering of all resource types, and require that each thread requests resources in an increasing order of enumeration

Circular Wait

- Invalidating the circular wait condition is most common.
- Simply assign each resource (i.e., mutex locks) a unique number.
- Resources must be acquired in order.
- If:

  `first_mutex = 1`
  `second_mutex = 5`

  code for **`thread_two`** could not be written as follows:

```
/* 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);
}
```

Deadlock Avoidance

Requires that the system has some additional ***a priori*** information available

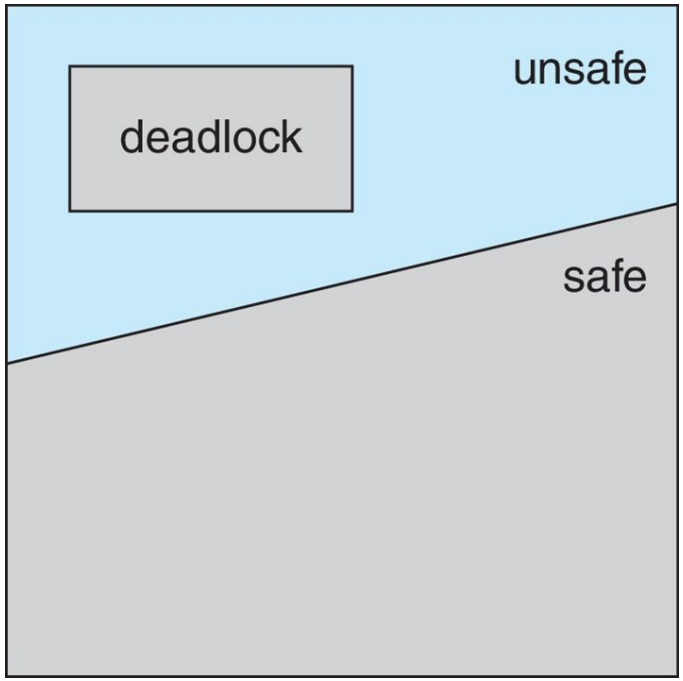
- Simplest and most useful model requires that each thread declare the ***maximum number*** of resources of each type that it may need
- The deadlock-avoidance algorithm dynamically examines the resource-allocation state to ensure that there can never be a circular-wait condition
- Resource-allocation *state* is defined by the number of available and allocated resources, and the maximum demands of the processes

Safe State

- When a thread requests an available resource, system must decide if immediate allocation leaves the system in a safe state
- System is in **safe state** if there exists a sequence $<T_1, T_2, \ldots, T_n>$ of ALL the threads in the systems such that for each T_i, the resources that T_i can still request can be satisfied by currently available resources + resources held by all the T_j, with $j < I$
- That is:
  - If T_i resource needs are not immediately available, then T_i can wait until all T_j have finished
  - When T_j is finished, T_i can obtain needed resources, execute, return allocated resources, and terminate
  - When T_i terminates, T_{i+1} can obtain its needed resources, and so on

Basic Facts

- If a system is in safe state ⇒ no deadlocks
- If a system is in unsafe state ⇒ possibility of deadlock
- Avoidance ⇒ ensure that a system will never enter an unsafe state.



Safe, Unsafe, Deadlock State

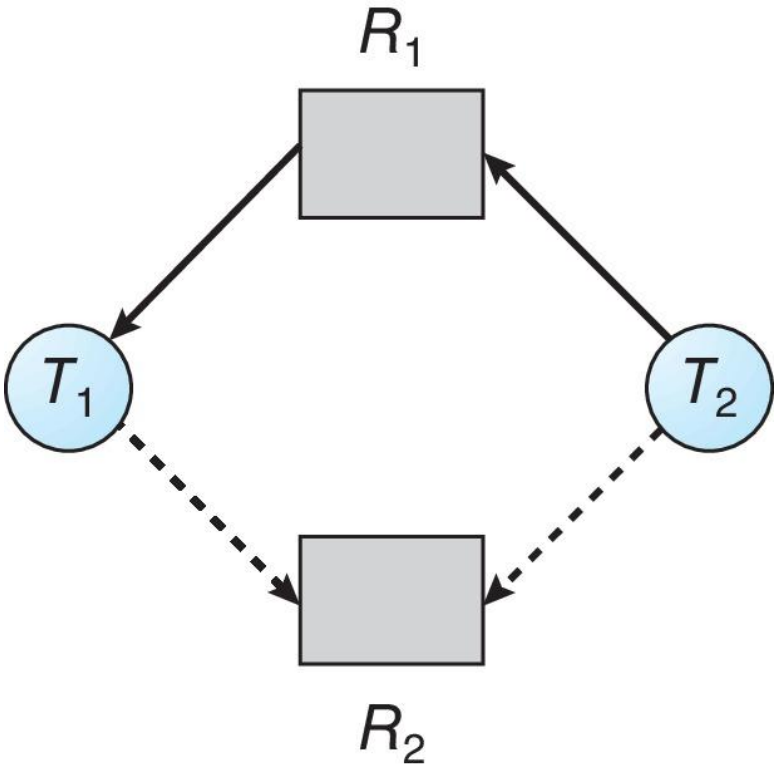
Avoidance Algorithms

- Single instance of a resource type
  - Use a resource-allocation graph
- Multiple instances of a resource type
  - Use the Banker's Algorithm

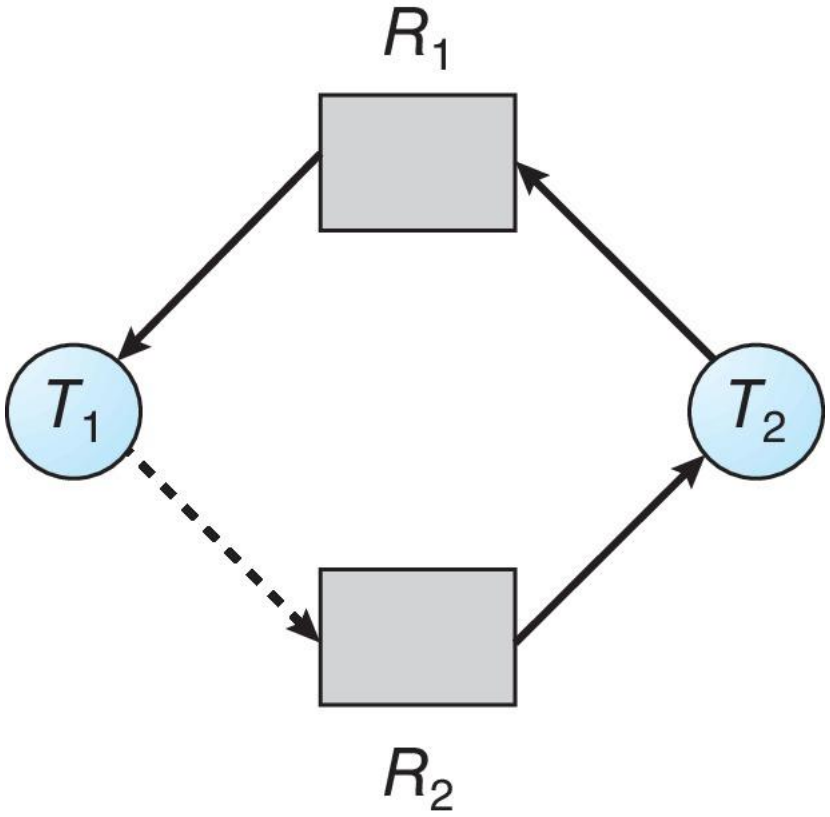
Resource-Allocation Graph Scheme

- **Claim edge** T_i - - > R_j indicated that process T_j may request resource R_j; represented by a dashed line
- Claim edge converts to request edge when a thread requests a resource
- Request edge converted to an assignment edge when the resource is allocated to the thread
- When a resource is released by a thread, assignment edge reconverts to a claim edge
- Resources must be claimed *a priori* in the system

Resource-Allocation Graph



Unsafe State In Resource-Allocation Graph



Resource-Allocation Graph Algorithm

- Suppose that thread T_i requests a resource R_j
- The request can be granted only if converting the request edge to an assignment edge does not result in the formation of a cycle in the resource allocation graph

Banker's Algorithm

- **Multiple instances** of resources
- Each thread must a priori claim **maximum use**
- When a thread **requests** a resource, it may have **to wait**
- When a thread gets all its resources it **must return them in a finite** amount of time

Data Structures for the Banker's Algorithm

Let n = number of processes, and m = number of resources types.

- **Available**: Vector of length m. If available $[j] = k$, there are k instances of resource type R_j available //represents the available instances of each resource type.

- **Max**: $n \times m$ matrix. If $Max[i,j] = k$, then process T_i may request at most k instances of resource type R_j specifies the maximum demand of each process for each resource type

- **Allocation**: $n \times m$ matrix. If $Allocation[i,j] = k$ then T_i is currently allocated k instances of R_j represents the resources currently allocated to each process.

- **Need**: $n \times m$ matrix. If $Need[i,j] = k$, then T_i may need k more instances of R_j to complete its task indicates the remaining resource need of each process to complete its task. It is calculated as the difference between the maximum demand (Max) and the currently allocated resources (Allocation).
  $Need[i,j] = Max[i,j] - Allocation[i,j]$

Safety Algorithm

This algorithm describes the Banker's Algorithm **for detecting a safe state in** a resource allocation scenario

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

   Work* = *Available //initialized with the available resources

   ***Finish* [*i*] = *false* for *i* = 0, 1, …, *n*- 1 //**initialized with false for each process, indicating that none of the processes have finished yet**.**

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

   (a) ***Finish* [*i*] = *false* //**This means the process i has not yet finished.

   (b) $Need_i \leq Work$ // This condition ensures that the process i can be completed with the available resources.

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

2. $Work = Work + Allocation_i$

   Finish*[*i*] = *true

   go to step 2 //If a process i is found that meets the criteria, resources are allocated to it by updating the Work vector.

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

Resource-Request Algorithm for Process P_i

$\boldsymbol{Request_i}$ = request vector for process $\boldsymbol{T_i}$. If $\boldsymbol{Request_i[j] = k}$ then process $\boldsymbol{T_i}$ wants $\boldsymbol{k}$ instances of resource type $\boldsymbol{R_j}$

1. If $\boldsymbol{Request_i \leq Need_i}$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim
2. If $\boldsymbol{Request_i \leq Available}$, go to step 3. Otherwise $\boldsymbol{T_i}$ must wait, since resources are not available
3. Pretend to allocate requested resources to $\boldsymbol{T_i}$ 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 ⇒ the resources are allocated to $\boldsymbol{T_i}$
- If unsafe ⇒ $\boldsymbol{T_i}$ must wait, and the old resource-allocation state is restored

Example of Banker's Algorithm

- 5 threads T_1 through T_5;

  3 resource types:

  A **(10 instances),** *B* (**5instances**), and *C* (**7 instances**)

- Snapshot at time T_0:

	Allocation	*Max*	*Available*	*Remaining need*
	A B C	*A B C*	*A B C*	*A B C*
T_1	0 1 0	7 5 3	**3 3 2**	7 4 3
T_2	2 0 0	3 2 2	5 3 2	1 2 2
T_3	3 0 2	9 0 2	7 4 3	6 0 0
T_4	2 1 1	4 2 2	7 4 5	2 1 1
T_5	0 0 2	5 3 3	7 5 5	5 3 1

---

7 2 5 10 5 7(All resources are released)

Available=(Total Resources-Allocation)

Remaining Need= Max need- Allocation

Example (Cont.)

- The content of the matrix ***Need*** is defined to be ***Max – Allocation***

	Need
	A B C
T_1	7 4 3
T_2	1 2 2
T_3	6 0 0
T_4	2 1 1
T_5	5 3 1

- The system is in a safe state since the sequence $< T_2, T_4, T_5, T_1, T_3 >$ satisfies safety criteria

Example: P_1 Request (1,0,2)

- Check that Request ≤ Available (that is, (1,0,2) ≤ (3,3,2) ⇒ true

	Allocation	*Need*	*Available*
	A B C	*A B C*	*A B C*
T_0	0 1 0	7 4 3	2 3 0
T_1	3 0 2		0 2 0
T_2	3 0 2	6 0 0	
T_3	2 1 1	0 1 1	
T_4	0 0 2	4 3 1	

- Executing safety algorithm shows that sequence < T_1, T_3, T_4, T_0, T_2> satisfies safety requirement
- Can request for (3,3,0) by T_4 be granted?
- Can request for (0,2,0) by T_0 be granted?

Practice

- https://www.gatevidyalay.com/deadlock-in-os-deadlock-problems-questions/
- https://www.scribd.com/document/334526647/Deadlock-Exercise-with-solution
- https://www.studocu.com/row/document/the-university-of-lahore/database-management-systems/os-ass3-operating-system-deadlock-related-assignment/10410496

** Practice exercise from chapter 8 of the book

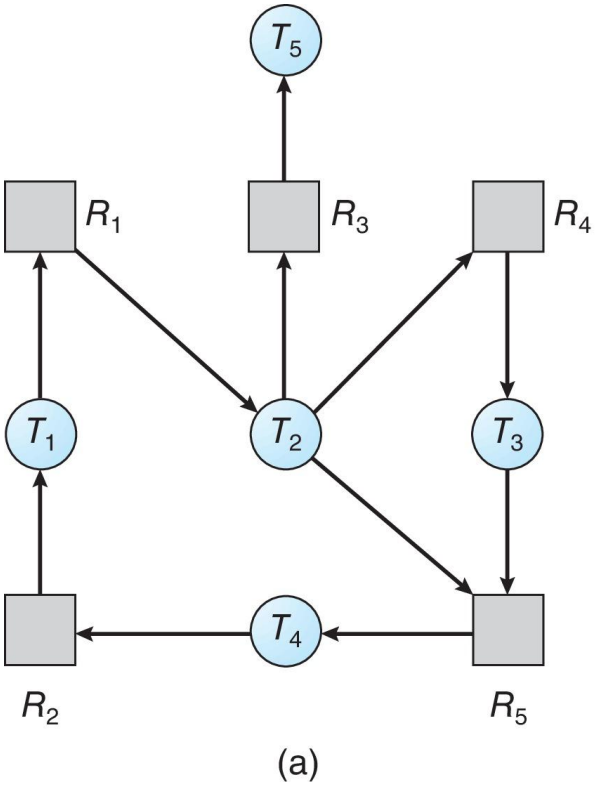
Deadlock Detection

- Allow system to enter deadlock state
- Detection algorithm
- Recovery scheme

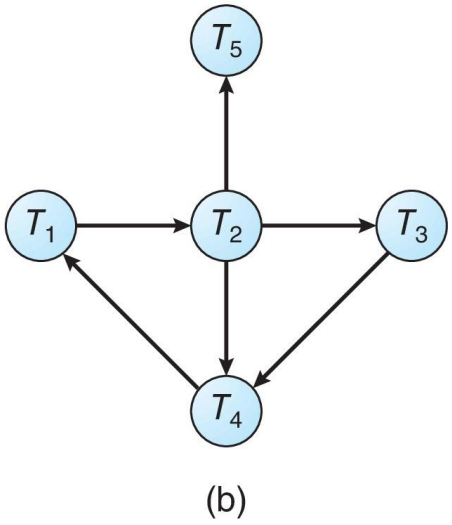
Single Instance of Each Resource Type

- Maintain **wait-for** graph
  - Nodes are threads
  - $T_i \rightarrow T_j$ if T_i is waiting for T_j
- Periodically invoke an algorithm that searches for a cycle in the graph. If there is a cycle, there exists a deadlock
- An algorithm to detect a cycle in a graph requires an order of n^2 operations, where n is the number of vertices in the graph

Resource-Allocation Graph and Wait-for Graph



Resource-Allocation Graph



Corresponding wait-for graph

Several Instances of a Resource Type

- **Available**: A vector of length ***m*** indicates the number of available resources of each type
- **Allocation**: An ***n*** **x** ***m*** matrix defines the number of resources of each type currently allocated to each thread.
- **Request**: An ***n*** **x** ***m*** matrix indicates the current request of each thread. If ***Request*** **[*i*][*j*] = *k***, then thread T_i is requesting ***k*** more instances of resource type R_j.

Detection Algorithm

1. Let ***Work*** and ***Finish*** be vectors of length ***m*** and ***n***, respectively Initialize:
   a) ***Work* = *Available***
   b) For ***i* = 1,2, …, *n***, if ***Allocation***$_i$ ≠ **0**, then ***Finish*[i] = *false***; otherwise, ***Finish*[i] = *true***

2. Find an index ***i*** such that both:
   a) ***Finish*[*i*] == *false***
   b) ***Request***$_i$ ≤ ***Work***

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

Detection Algorithm (Cont.)

3. ***Work = Work + Allocation***$_i$
   Finish*[*i*] = *true
   go to step 2

4. If ***Finish[i] == false***, for some ***i***, $1 \le i \le n$, then the system is in deadlock state. Moreover, if ***Finish*[*i*] == *false***, then T_i is deadlocked

Algorithm requires an order of O(m x n^2) operations to detect whether the system is in deadlocked state

Example of Detection Algorithm

- Five threads T_0 through T_4; three resource types A (7 instances), *B* (2 instances), and *C* (6 instances)

- Snapshot at time T_0:

	Allocation	*Request*	*Available*
	A B C	*A B C*	*A B C*
T_0	0 1 0	0 0 0	0 0 0
T_1	2 0 0	2 0 2	
T_2	3 0 3	0 0 0	
T_3	2 1 1	1 0 0	
T_4	0 0 2	0 0 2	

- Sequence <T_0, T_2, T_3, T_1, T_4> will result in ***Finish[i] = true*** for all ***i***

Example (Cont.)

- T_2 requests an additional instance of type ***C***

	Request
	A B C
T_0	0 0 0
T_1	2 0 2
T_2	0 0 1
T_3	1 0 0
T_4	0 0 2

- State of system?
  - Can reclaim resources held by thread T_0, but insufficient resources to fulfill other processes; requests
  - Deadlock exists, consisting of processes T_1, T_2, T_3, and T_4

Detection-Algorithm Usage

- When, and how often, to invoke depends on:
  - How often a deadlock is likely to occur?
  - How many processes will need to be rolled back?
    - one for each disjoint cycle
- If detection algorithm is invoked arbitrarily, there may be many cycles in the resource graph and so we would not be able to tell which of the many deadlocked threads “caused” the deadlock.

Recovery from Deadlock: Process Termination

- Abort all deadlocked threads
- Abort one process at a time until the deadlock cycle is eliminated
- In which order should we choose to abort?
  1. Priority of the thread
  2. How long has the thread computed, and how much longer to completion
  3. Resources that the thread has used
  4. Resources that the thread needs to complete
  5. How many threads will need to be terminated
  6. Is the thread interactive or batch?

Recovery from Deadlock: Resource Preemption

- **Selecting a victim** – minimize cost
- **Rollback** – return to some safe state, restart the thread for that state
- **Starvation** – same thread may always be picked as victim, include number of rollback in cost factor

End of Chapter 8