

Sistemi Operativi I

Corso di Laurea in Informatica
2024-2025



SAPIENZA
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Recap from Last Lecture

- Synchronization primitives:
 - Locks
 - Semaphores
 - Monitors

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- Synchronization primitives:
 - Locks
 - Semaphores
 - Monitors
- 2 fundamental synchronization problems:
 - Producers-Consumers
 - Readers-Writers

Our Journey

- What is deadlock?
- Conditions for deadlock to happen
- Deadlock detection
- Deadlock prevention
- Deadlock avoidance

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What is Deadlock?

“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.”

Kansas legislation early 1900's

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Intuitively, a condition where two or more threads are waiting for an event that can only be generated by the very same threads

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Thread A

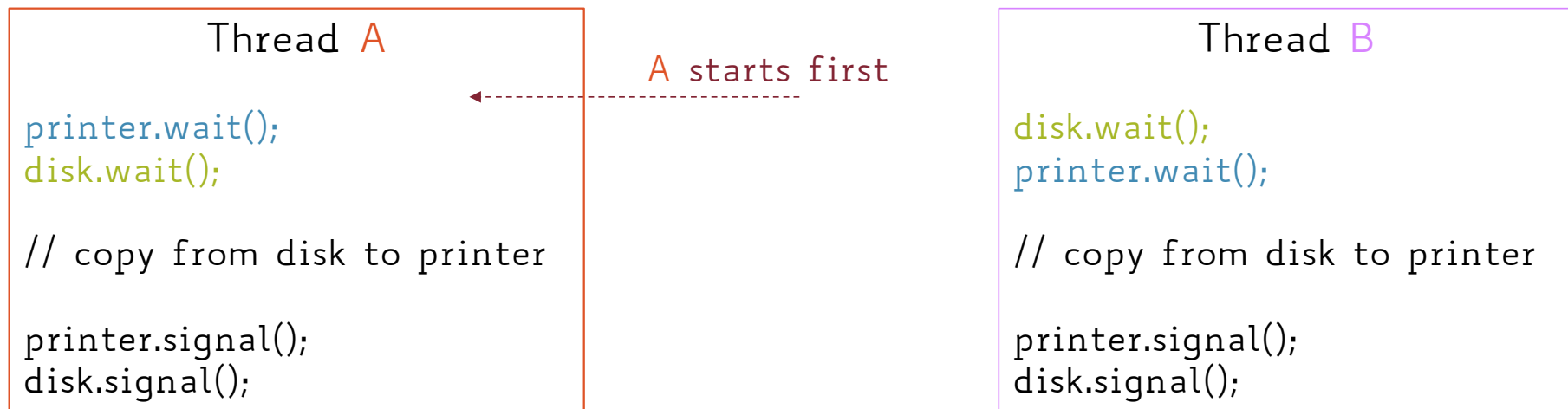
```
printer.wait();  
disk.wait();  
  
// copy from disk to printer  
  
printer.signal();  
disk.signal();
```

Thread B

```
disk.wait();  
printer.wait();  
  
// copy from disk to printer  
  
printer.signal();  
disk.signal();
```


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Thread A

```
printer.wait(); Acquires printer and context switch  
disk.wait();
```



```
// copy from disk to printer
```

```
printer.signal();  
disk.signal();
```

Thread B

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printer.wait();
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printer.signal();  
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disk.wait();  
  
// copy from disk to printer  
  
printer.signal();  
disk.signal();
```

B takes over

Thread B

```
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printer.wait();  
  
// copy from disk to printer  
  
printer.signal();  
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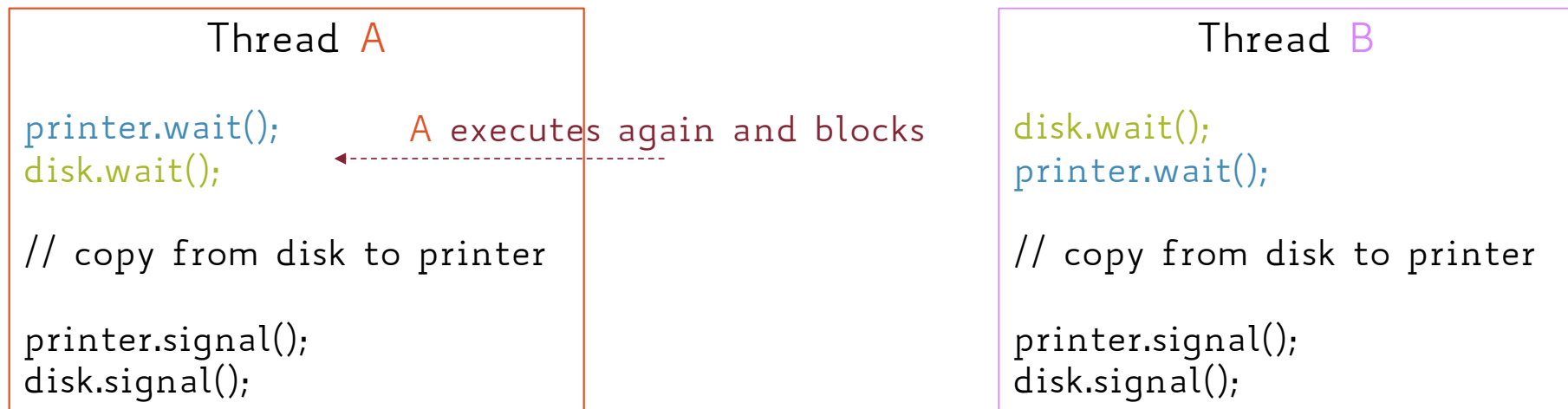
Thread B

```
disk.wait();  
printer.wait();  
  
// copy from disk to printer  
  
printer.signal();  
disk.signal();
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Acquires disk and
context switch

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B executes again and blocks

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A waits B to release the disk

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B waits A to release the printer

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- **Deadlock avoidance (online)**: runtime support checks resource requests made by threads to avoid deadlocks

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- Not to be confused with each other!
- Related terms but each one refers to a specific situation
- Starvation occurs when a thread waits indefinitely for some resource but other threads are actually making progress using that resource
- The main difference with deadlock is that the system is not completely stuck!

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Necessary Conditions for Deadlock

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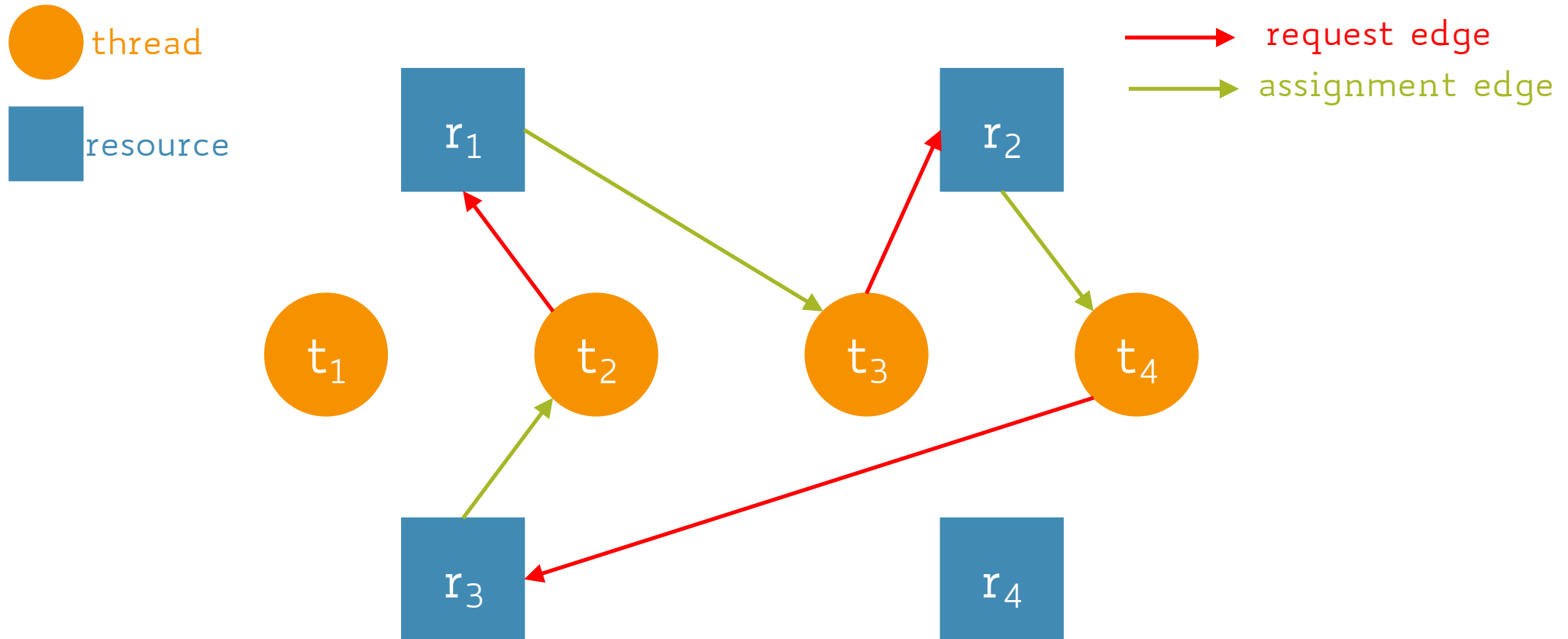
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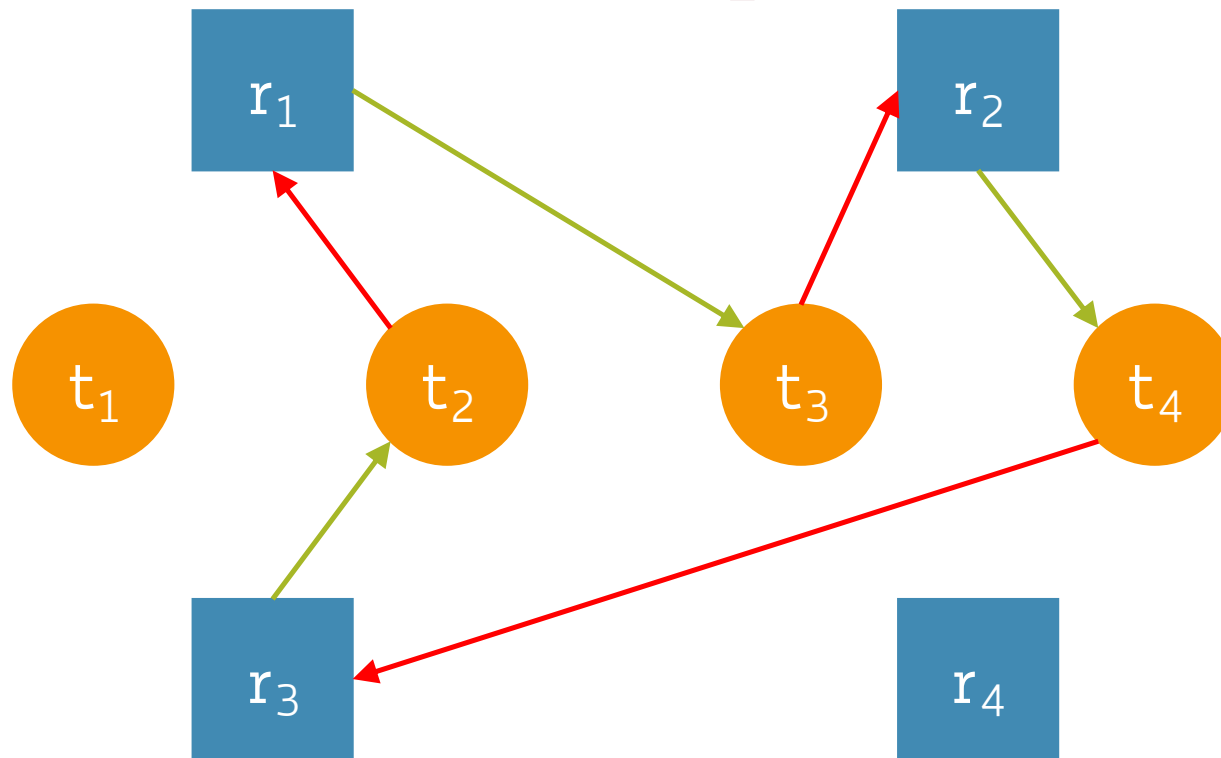
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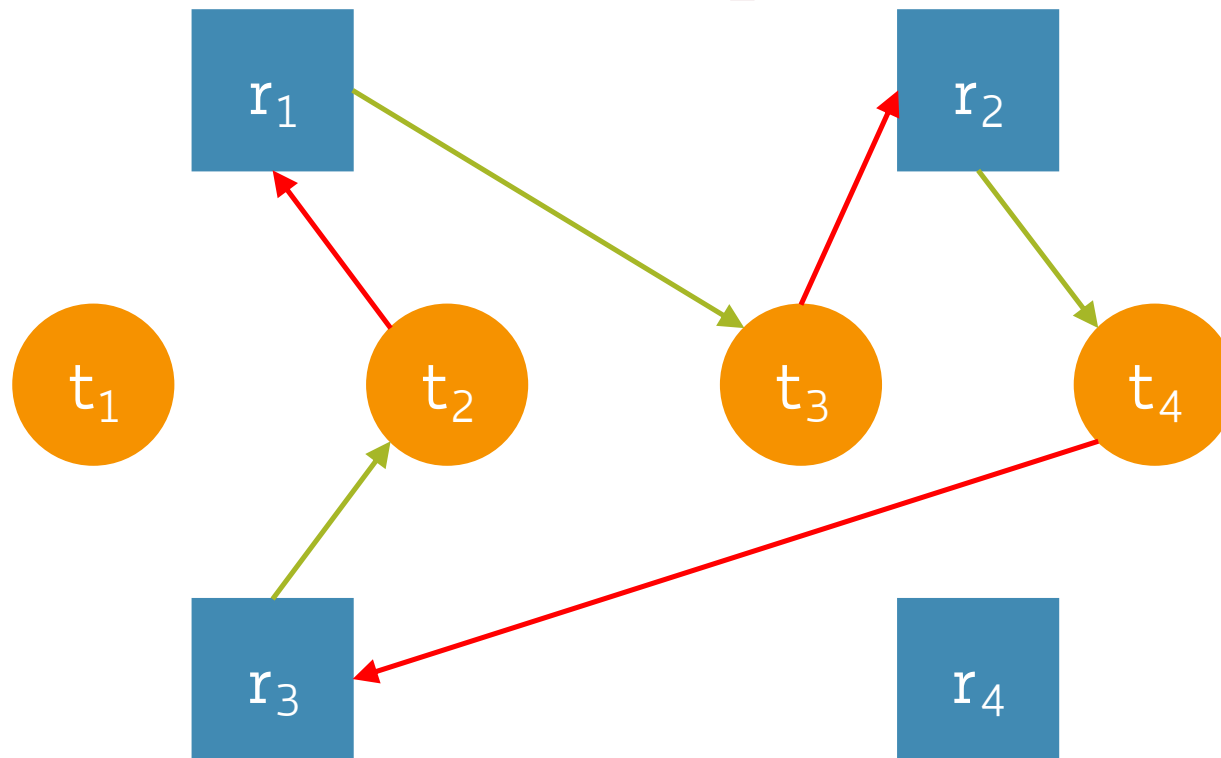


Deadlock Detection: Resource Allocation Graph



If the graph has no cycles, no deadlock will ever exist

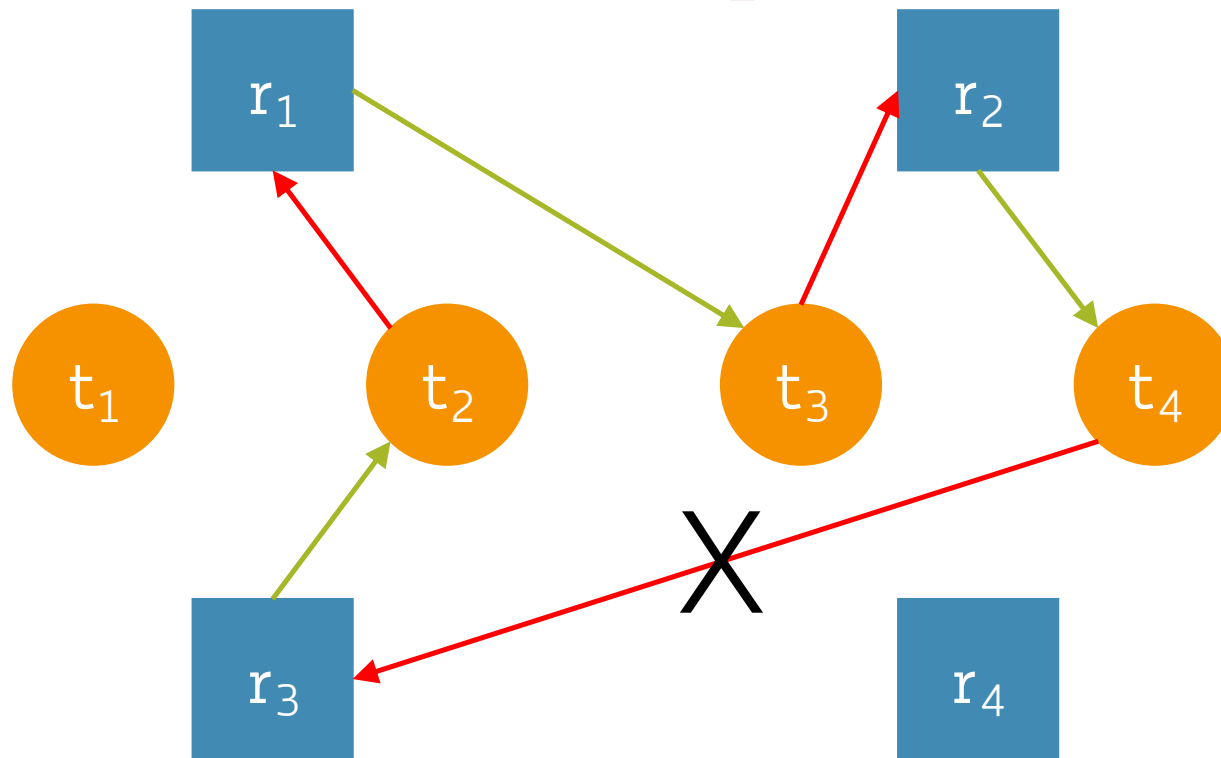
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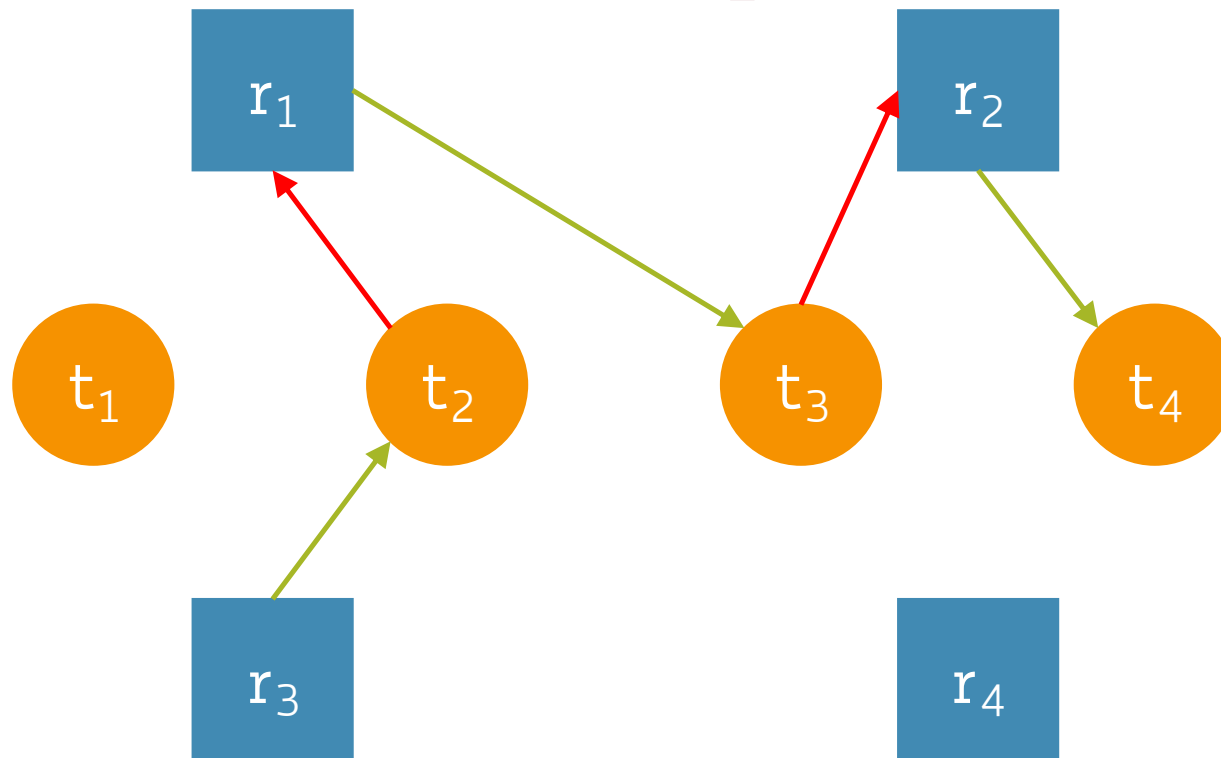
Why?

Deadlock Detection: Resource Allocation Graph



Suppose we remove the edge (t_4, r_3) so as to remove the cycle

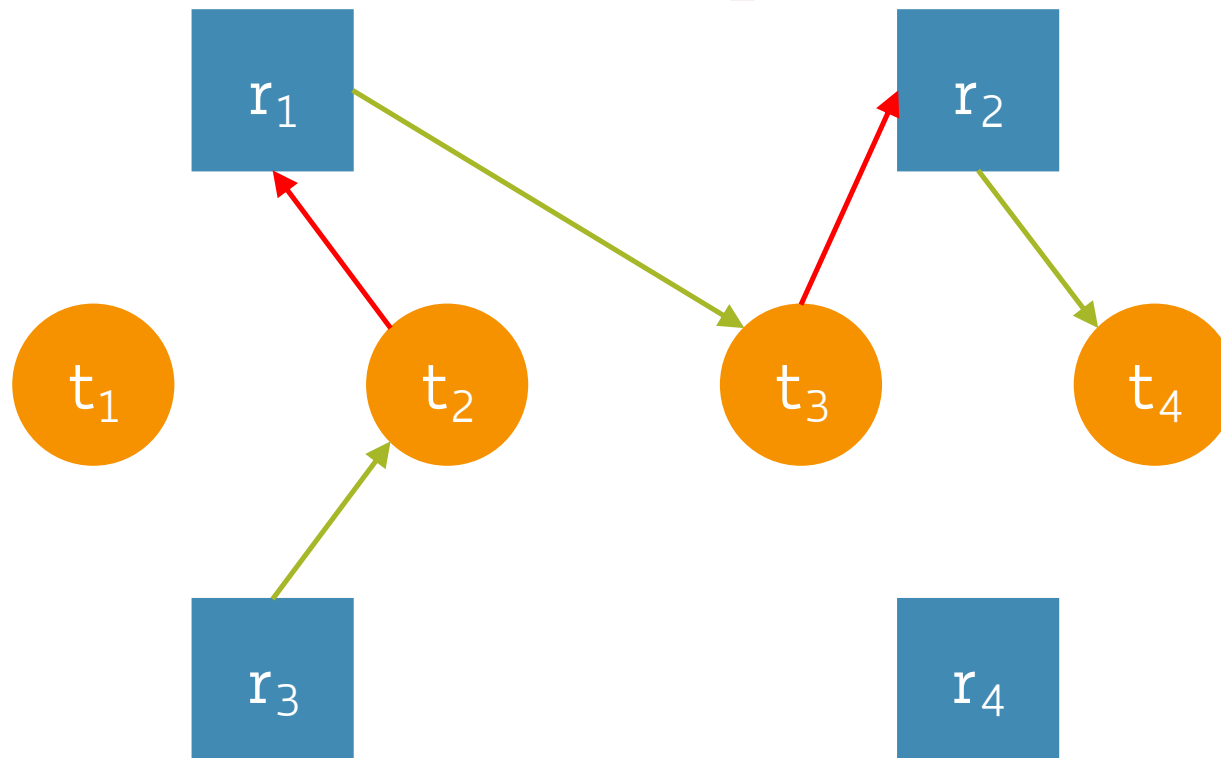
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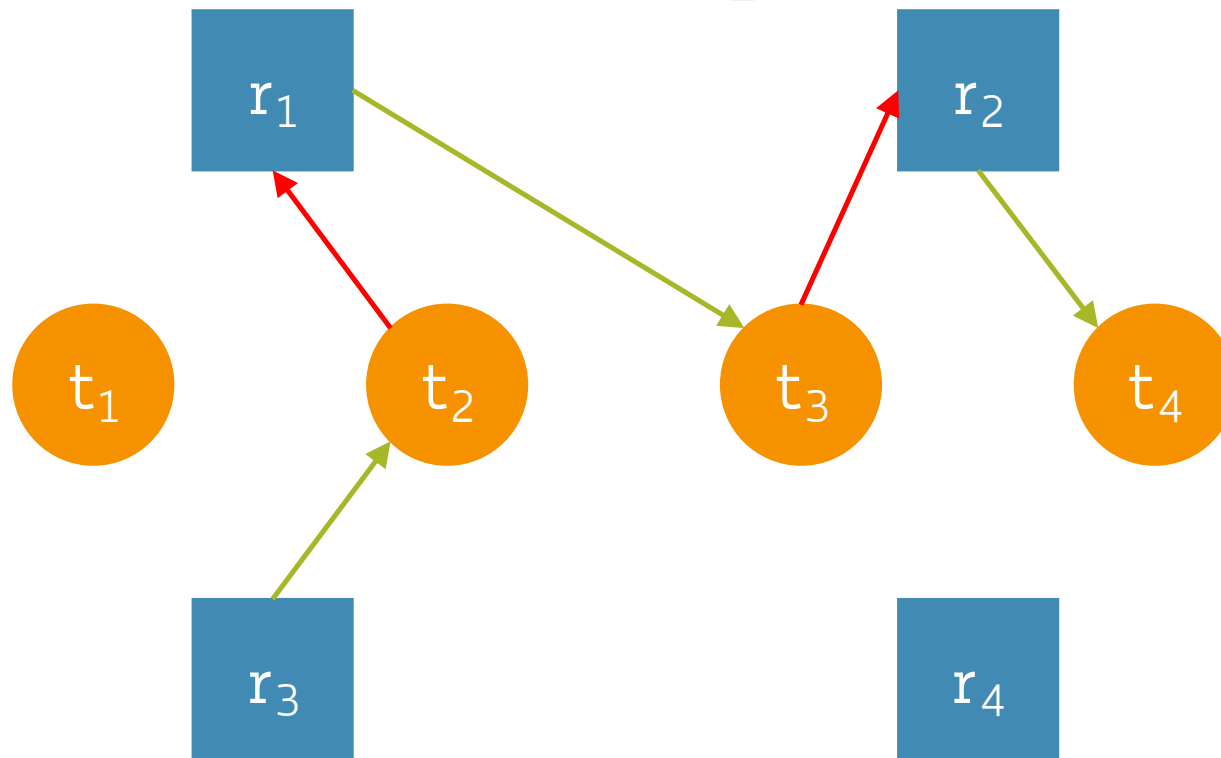


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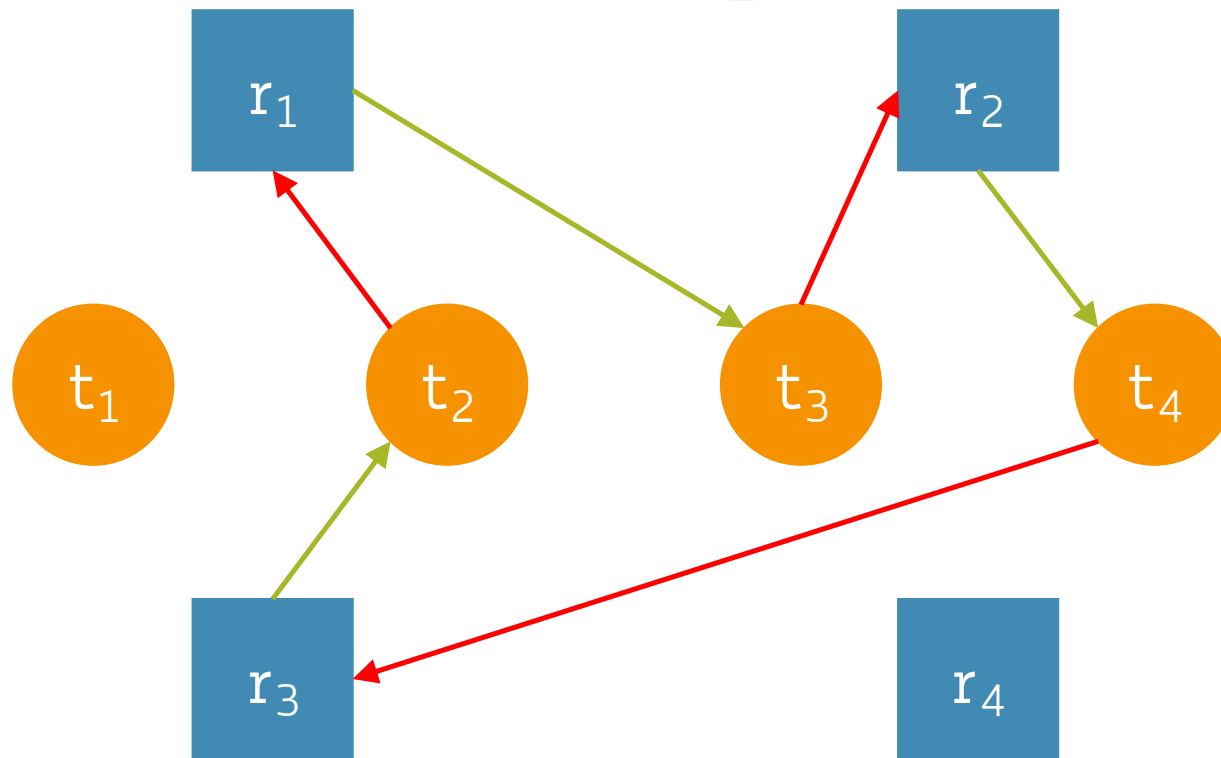
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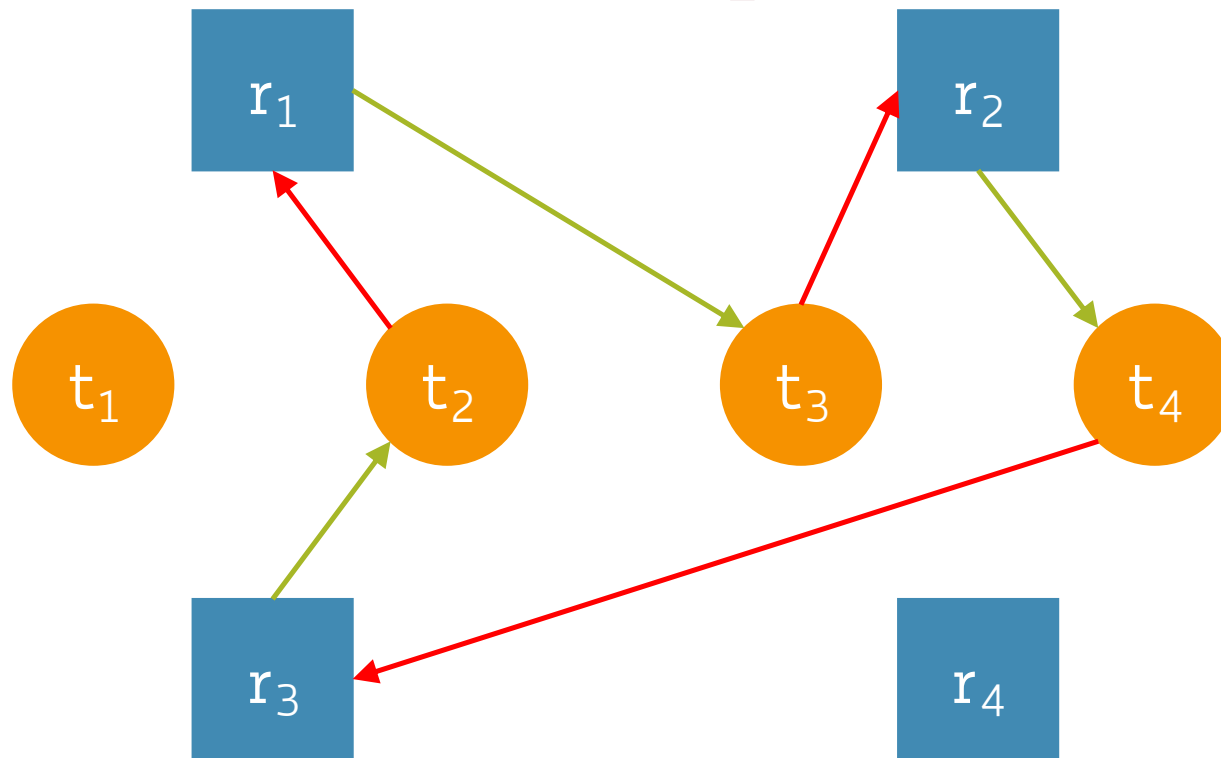
And so on and so forth...

Deadlock Detection: Resource Allocation Graph



If the graph has cycles, deadlock **might** exist

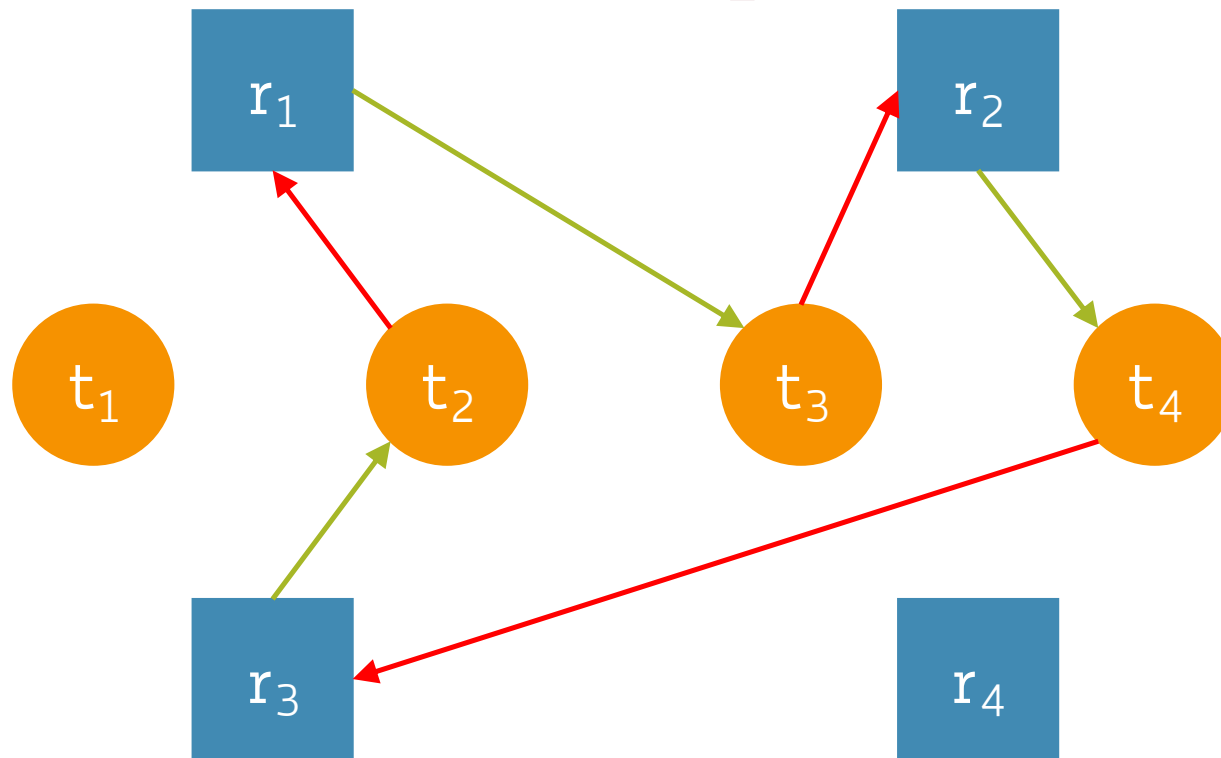
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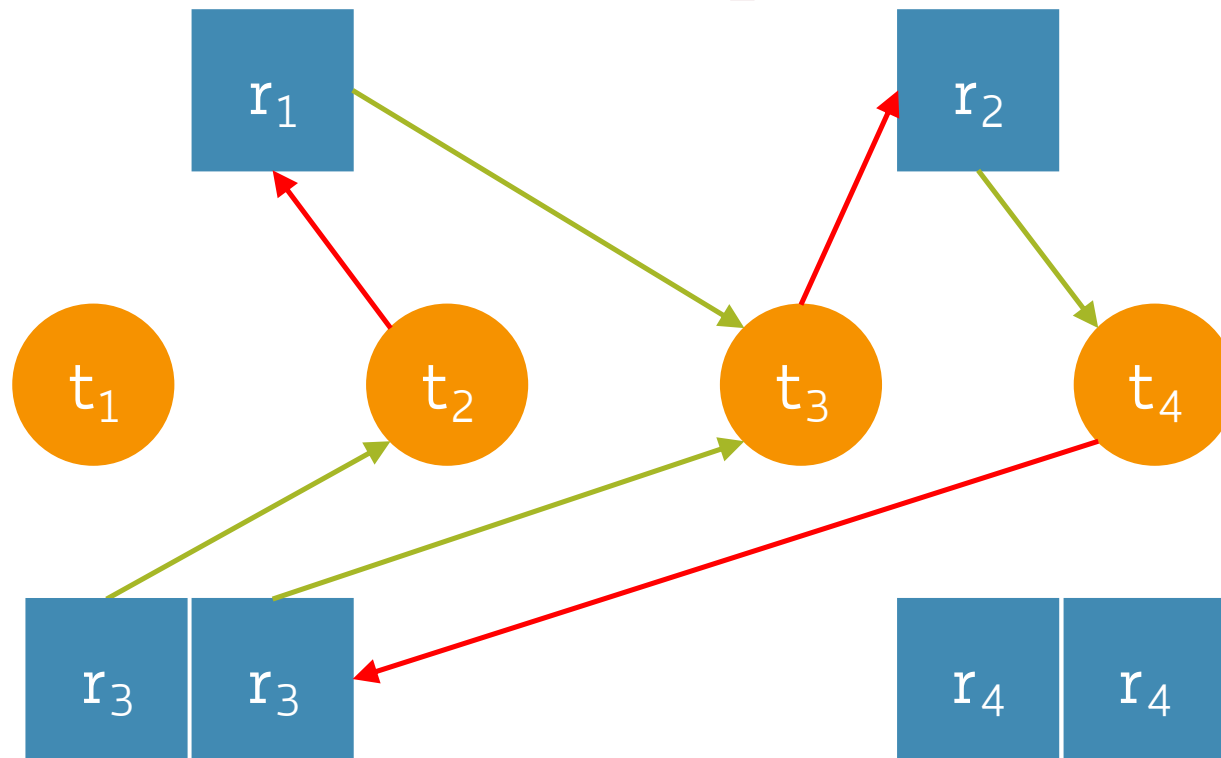
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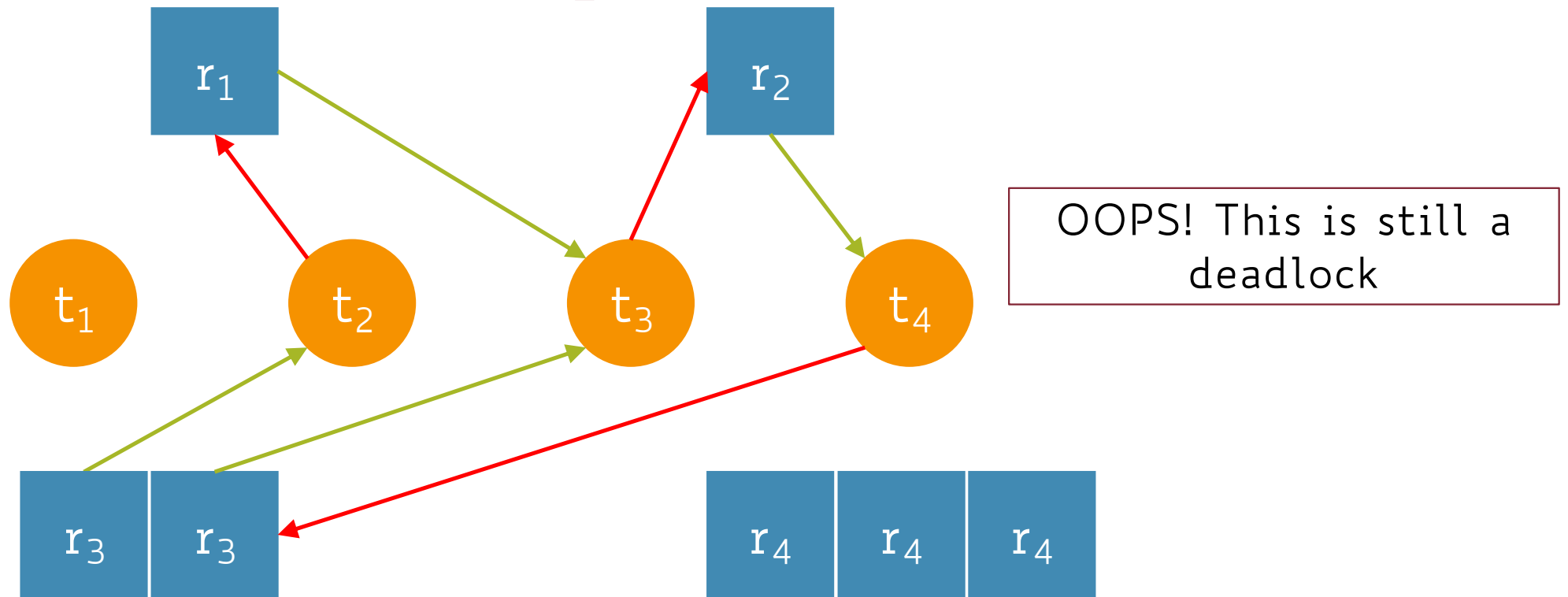
We are assuming the **multiplicity** of each resource is **1** (i.e., one r_1 , one r_2 , etc.)

Deadlock Detection: Resource Allocation Graph

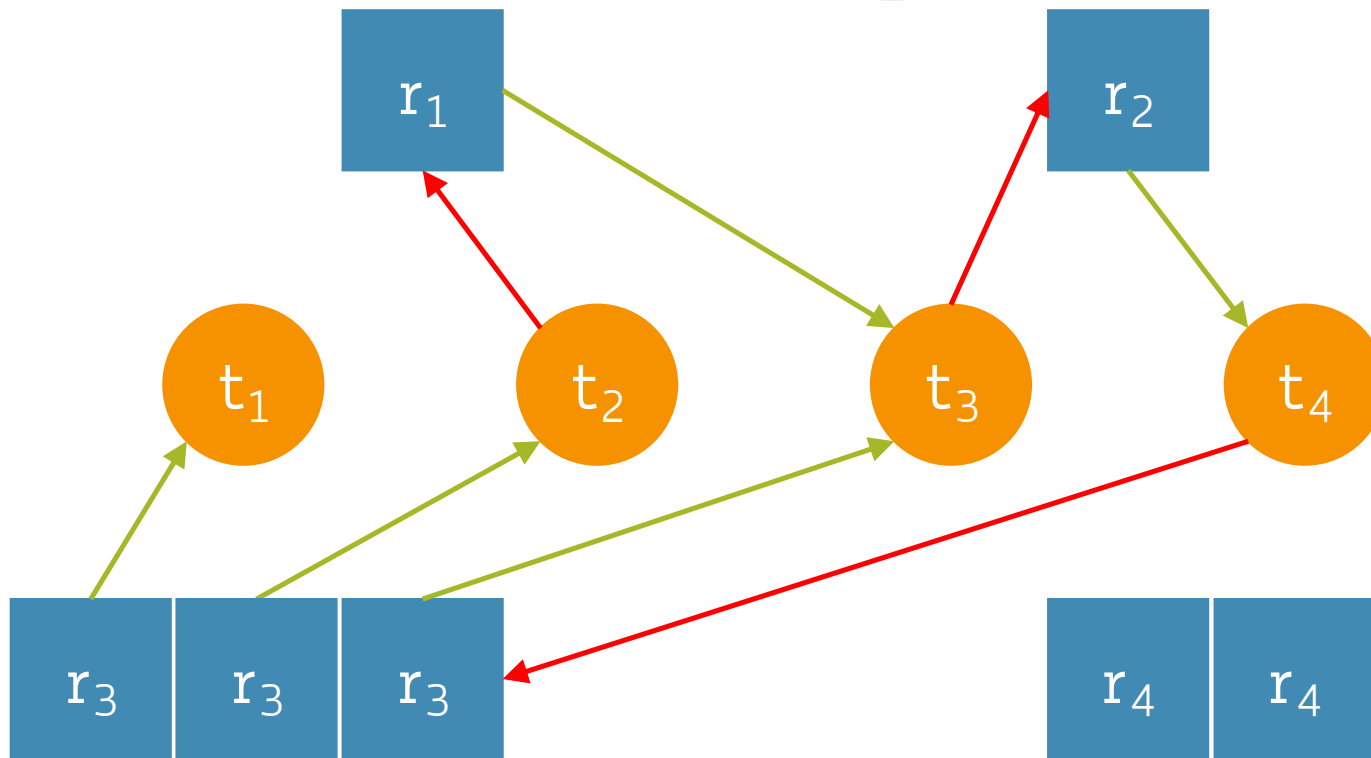


What if there are **multiple** instances of the same resource?

Deadlock Detection: Resource Allocation Graph



Deadlock Detection: Resource Allocation Graph



This works!
If **any** resource involved in the cycle is held by a thread which is not in the cycle (t_1) then we can make progress

Deadlock: Detect and Correct It!

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- We would like to be more precise than that...

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- Known algorithms based on **depth-first search (DFS)** take $O(|V|+|E|)$ time
- $O(|V|+|E|) \sim O(|V|^2)$ as $|E| = O(|V|^2)$ for dense graphs, and $|V| = \text{\#threads} + \text{\#resources}$

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- When to run such a detection algorithm?
 - Before granting a resource → each granted request will take $O(|V|^2)$
 - When a request cannot be fulfilled → each failed request will take $O(|V|^2)$
 - On a regular schedule or when the CPU is under-utilized

Our Journey

- What is deadlock?
- Conditions for deadlock to happen
- Deadlock detection
- **Deadlock prevention**
- Deadlock avoidance

Deadlock Prevention

- Ensure that at least one of the 4 necessary conditions doesn't hold
 - Mutual Exclusion → make all resources sharable
 - Not all can be shared
 - E.g., disks, printers, etc.

Deadlock Prevention

- Ensure that **at least one** of the **4** necessary conditions doesn't hold
 - **Hold and Wait** → a thread cannot hold one resource when it requests another
 - Enforce requests to be made all at once
 - Hard to predict all the resources a thread will need

Deadlock Prevention

- Ensure that **at least one** of the **4** necessary conditions doesn't hold
 - **No Preemption** → if a thread requests a resource that cannot be allocated to it, the OS preempts (releases) all the resources that the thread is already holding
 - Not all resources can be easily preempted (e.g., printers)

Deadlock Prevention

- Ensure that at least one of the 4 necessary conditions doesn't hold
 - Circular Wait → impose an ordering (i.e., numbering) on resources and enforce to request them in such order
 - Hard to establish such an order

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Deadlock Avoidance: Resource Reservation

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m_i = *maximum* number of resources that thread i *might* request

c_i = *current* number of resources that thread i is holding

$C = \sum_{i=1}^n c_i$ = *total* number of resources currently allocated

R = *maximum* number of resources overall available

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Any thread sequence is **safe** if for each thread it holds that:

$$\underbrace{m_i - c_i}_{\text{resources } t_i \text{ might still request}} \leq \underbrace{R - C}_{\text{resources currently available}} + \underbrace{\sum_{j=1}^{i-1} c_j}_{\text{resources currently allocated up to } t_j, j < i}$$

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- This policy ensures no circular-wait condition exists

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t_3 can use the current allocation, plus t_1 's & t_2 's resources and 1 drive left (8 drives)

Deadlock Avoidance: Example

Thread	m_i	c_i	$m_i - c_i$
t_1	4	3	1
t_2	8	4	4
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Suppose t_3 requests one more drive, then now there are **no more available drives**

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However, t_3 must wait because allocating that extra drive would lead to an unsafe state, which in turn might lead to deadlock

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 - Claim (dotted) Edge \rightarrow a directed edge (t_i, r_j) indicates that t_i might request r_j in the future
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- Satisfying a request means converting a claim into an assignment edge

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- If the allocation results in an unsafe state, this will be denied even if the resource is actually available

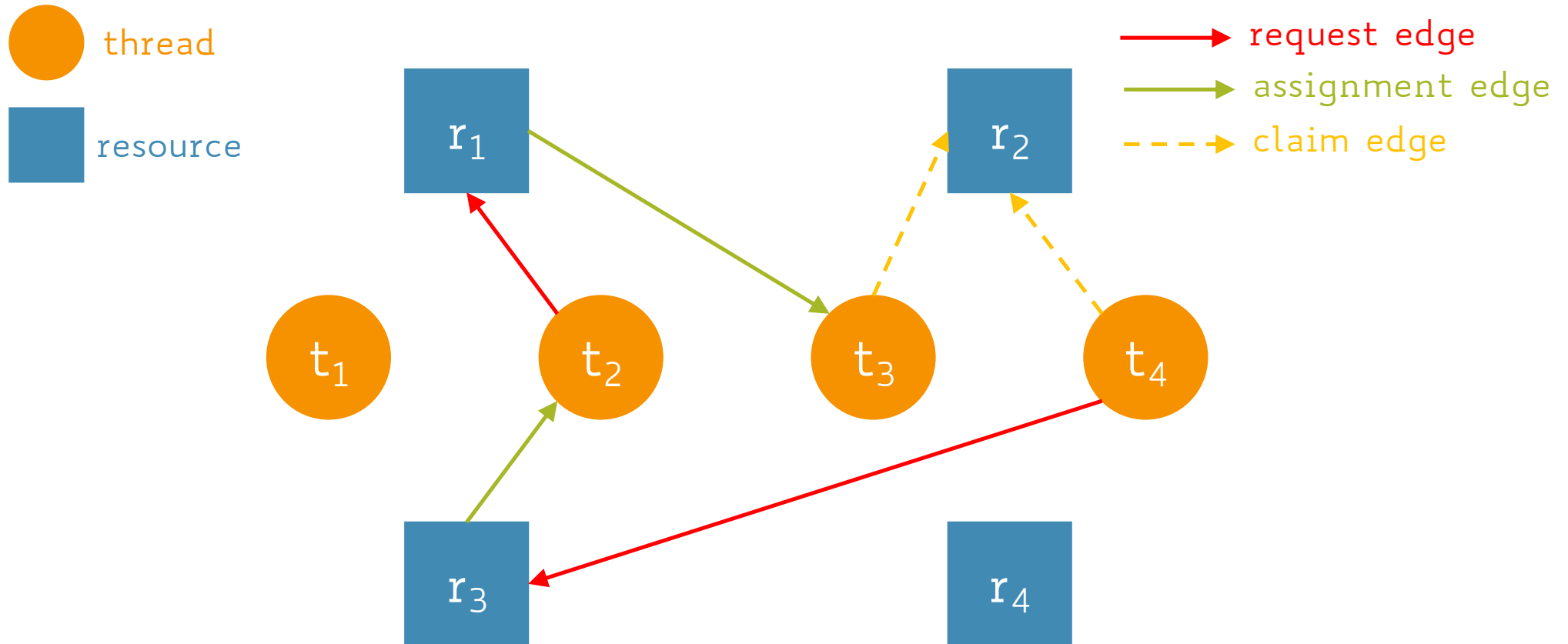
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- If the allocation results in an unsafe state, this will be denied even if the resource is actually available
- In other words, the claim edge is converted into a request edge and the thread will wait

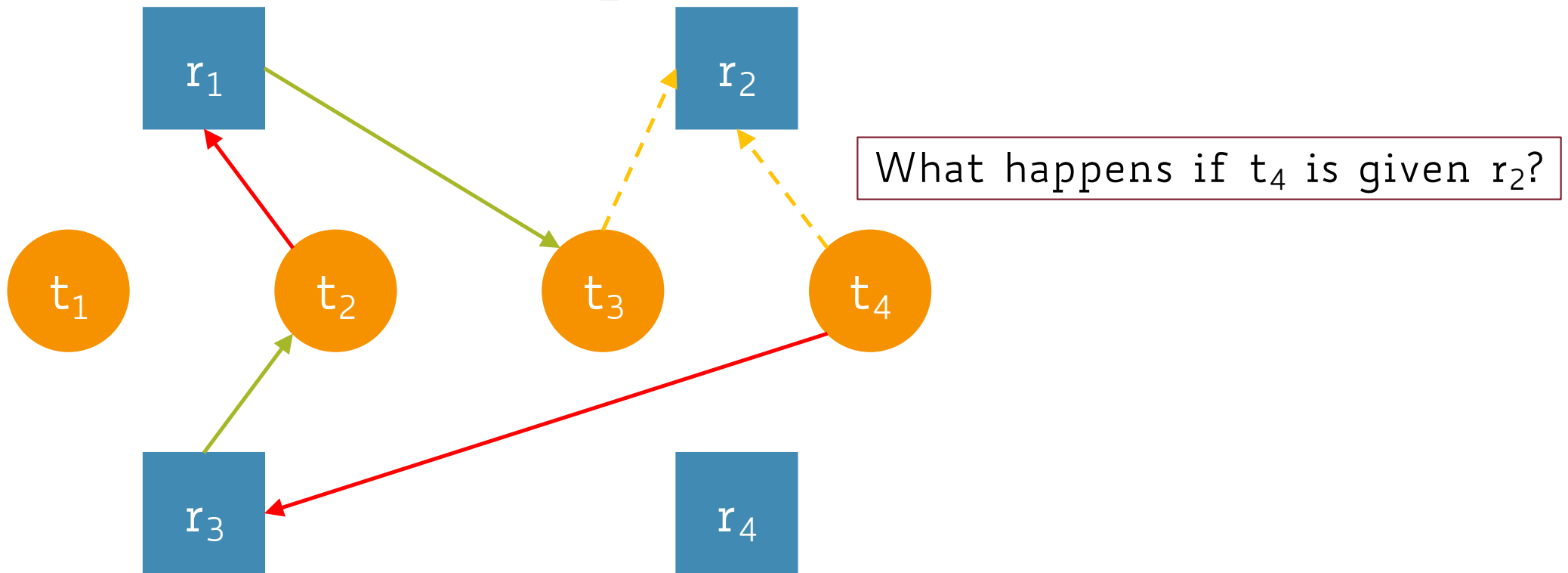
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- A cycle in this extended RAG indicates an unsafe state
- If the allocation results in an unsafe state, this will be denied even if the resource is actually available
- In other words, the claim edge is converted into a request edge and the thread will wait
- NOTE: This solution does not work when there are multiple instances of the **same** resource

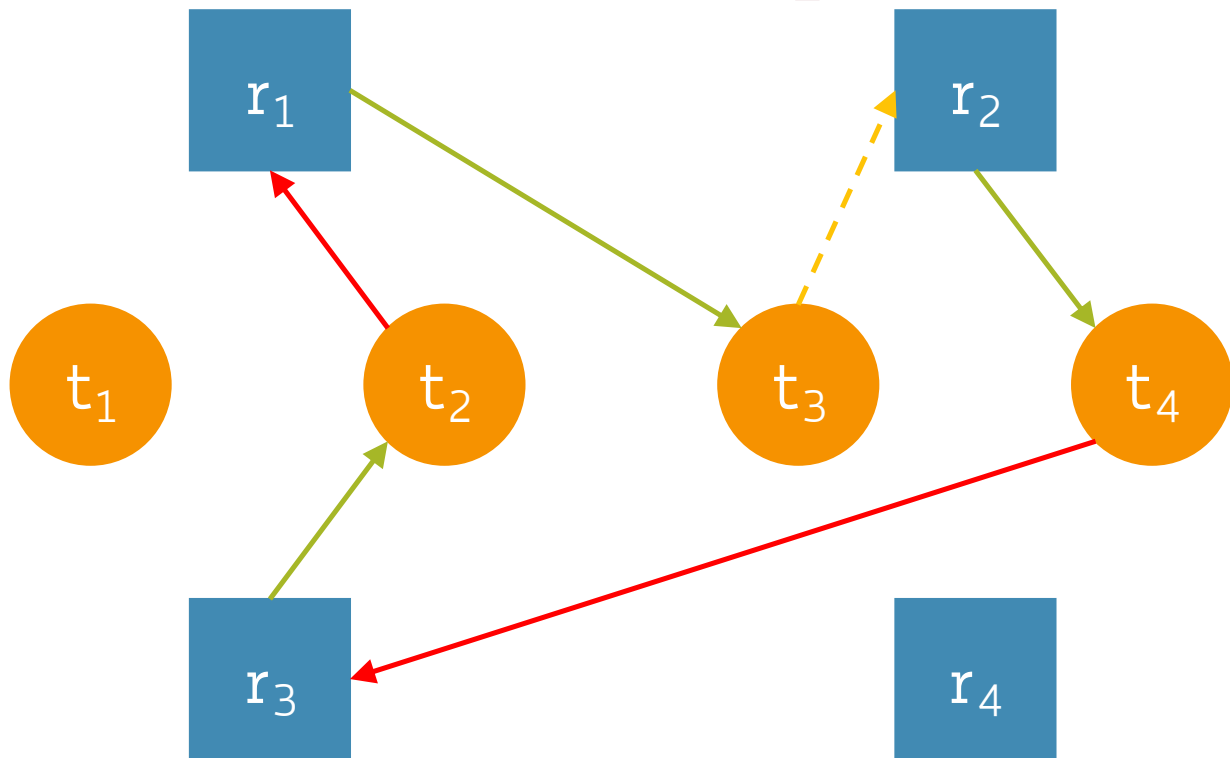
Deadlock Avoidance: Resource Allocation Graph



Deadlock Avoidance: Resource Allocation Graph



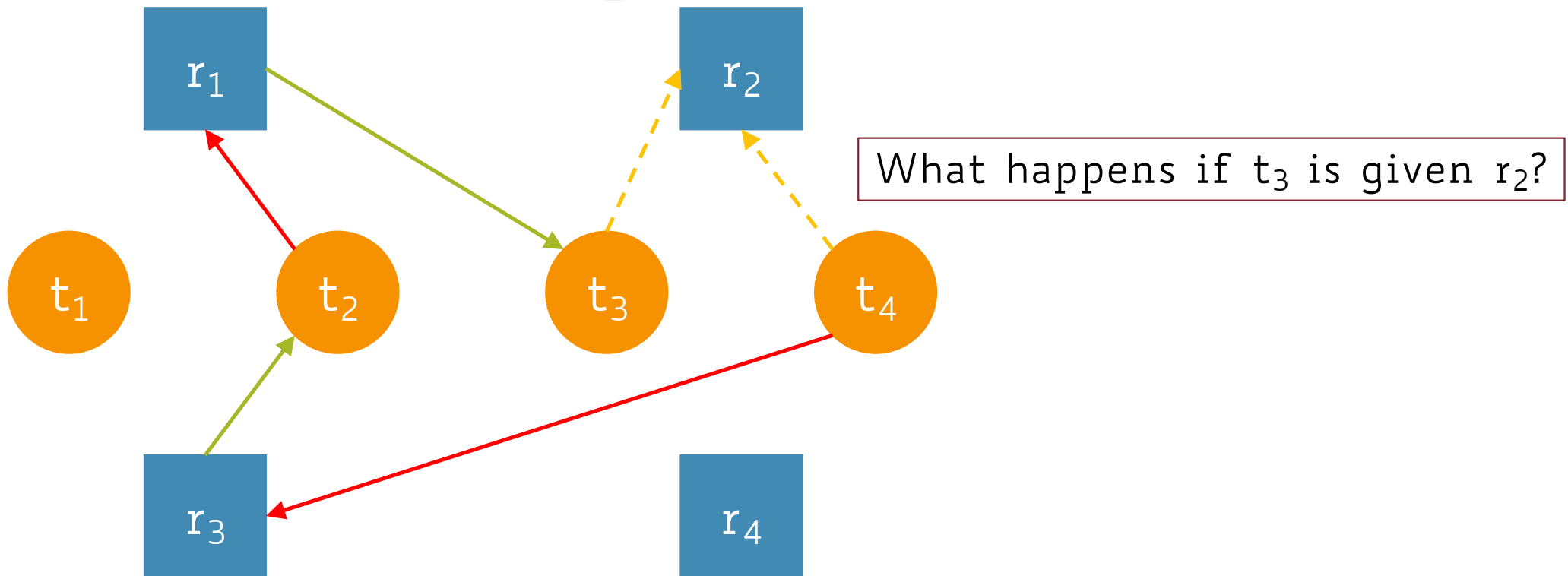
Deadlock Avoidance: Resource Allocation Graph



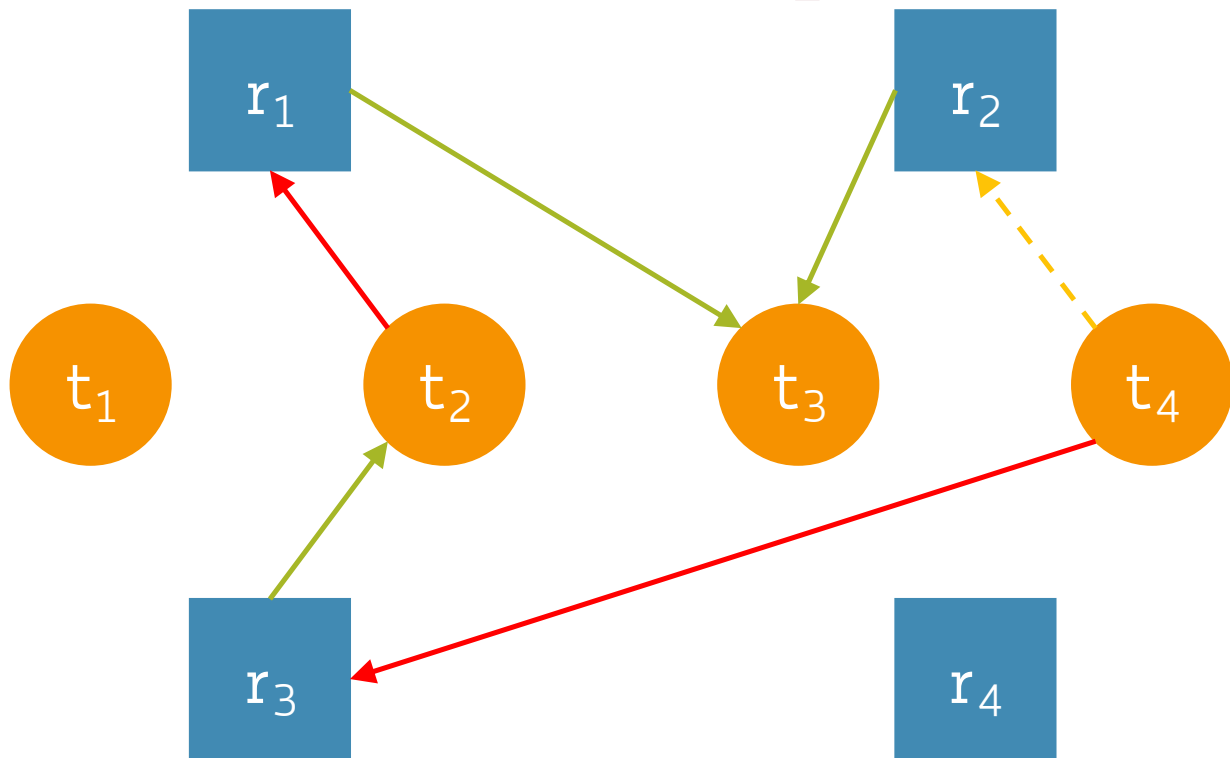
We are introducing a potential cycle (t_3 requests r_2), which in turn might cause deadlock

unsafe state

Deadlock Avoidance: Resource Allocation Graph



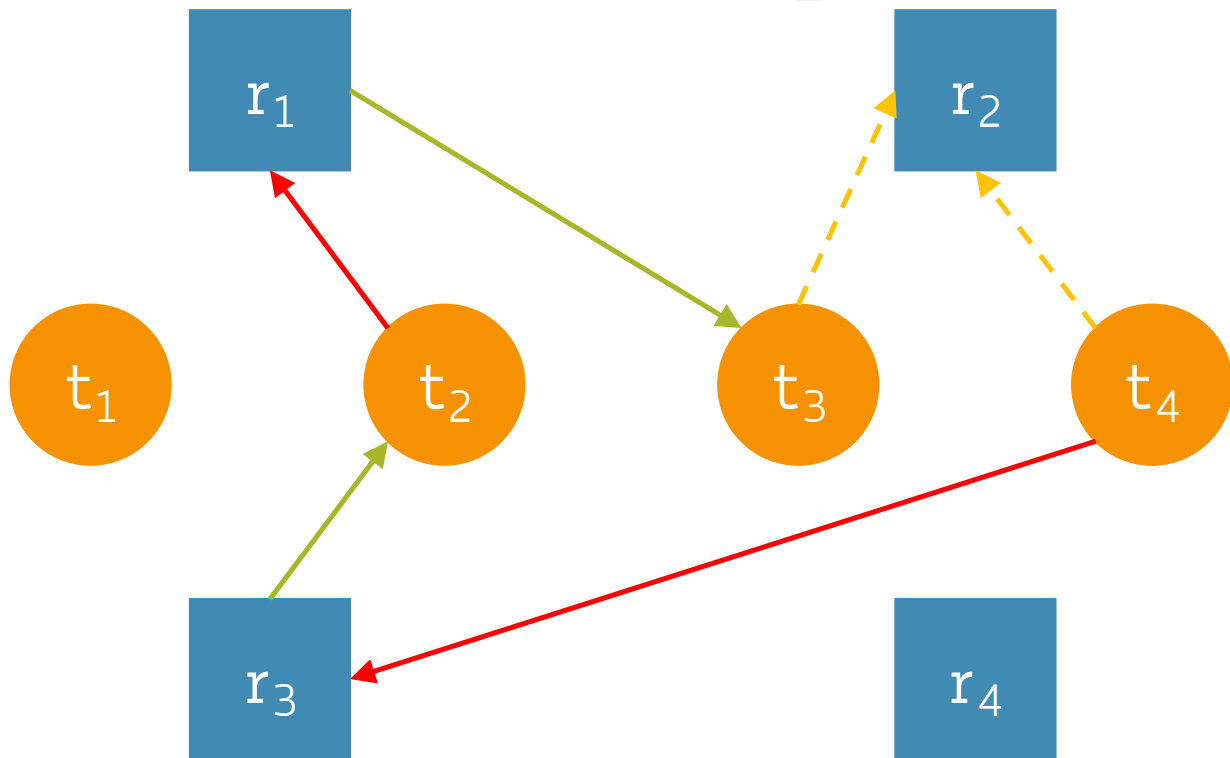
Deadlock Avoidance: Resource Allocation Graph



We are **not** introducing any potential cycle (t_4 requests r_2)

safe state

Deadlock Avoidance: Resource Allocation Graph



Start from a safe state

Invariant

Accept a request iff
we move from a safe
state to another

Banker's Algorithm

- Handles multiple instances of the same resource
- Forces threads to provide information on what resource they might need, in advance
- The resources requested must not exceed the total available in the system
- The algorithm allocates resources to a requesting thread if the allocation leaves the system in a safe state, otherwise the thread waits

Banker's Algorithm: Data Structures

- n = number of threads; m = number of resource types
- $available[1..m]$: m -dimensional vector
 - $available[j] = k$ means there are k resources of type j available
- $max[1..n, 1..m]$: $n \times m$ matrix
 - $max[i, j] = k$ means thread i may require at most k resources of type j
- $allocation[1..n, 1..m]$: $n \times m$ matrix
 - $allocation[i, j] = k$ means thread i has allocated k resources of type j
- $need[1..n, 1..m]$: $n \times m$ matrix
 - $need[i, j] = max[i, j] - allocation[i, j] = k$ means thread i may need k more resources of type j to complete its task

Banker's Algorithm: Idea

- The algorithm is divided in 2 tasks:
 - `isSafeState` → given the current status of allocation of resources, tests if this is a safe state
 - `resourceRequest` → given a thread and its resource request decides if such a request can be satisfied

Banker's Algorithm: Idea

- The algorithm is divided in 2 tasks:
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- A request can be satisfied iff this leads to a safe state!

Banker's Algorithm: Idea

- The algorithm is divided in 2 tasks:
 - `isSafeState` → given the current status of allocation of resources, tests if this is a safe state
 - `resourceRequest` → given a thread and its resource request decides if such a request can be satisfied
- A request can be satisfied iff this leads to a safe state!
- In other words, the second task uses the output of the first one in order to make a decision

Banker's Algorithm: isSafeState

1. Let work and finish be vectors of length m and n, respectively

Initialize: $work = available$; $finish[i] = false$; for all i

2. Find an i such that:

$finish[i] = false \ \&\& \ need[i] \leq work$

If no such i exists, go to step 4.

3. Assume thread i executes:

$work = work + allocation[i]$; $finish[i] = true$; go to step 2.

4. If $finish[i] == true$ for all i, the system is in a safe state

Banker's Algorithm: requestResource

Input: i (thread) and request an m -dimensional vector of requests

1. If $\text{request} > \text{need}[i]$ raise an error as thread i is attempting to request more resources than it claimed, otherwise go to step 2.
2. If $\text{request} > \text{available}$ thread i must wait since resources are not available, otherwise go to step 3.
3. Even if resources are available, test if this allocation will lead to a safe state by simulating it
 $\text{available} -= \text{request}; \text{allocation}[i] += \text{request}; \text{need}[i] -= \text{request};$
 $\text{isSafeState()} ? \text{OK} : \text{rollback()} \text{ and } \text{wait}()$

Banker's Algorithm: Example

A snapshot of the current state of the system

		RESOURCES								
		MAX			ALLOCATION			AVAILABLE		
		A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1			
	T ₁	1	7	5	1	0	0			
	T ₂	2	3	5	1	3	5			
	T ₃	0	6	5	0	6	3			
	Total				2	9	9	1	5	2

Banker's Algorithm: Example

Q1: How many resources of type A, B, and C are there overall?

		RESOURCES								
		MAX			ALLOCATION			AVAILABLE		
		A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1			
	T ₁	1	7	5	1	0	0			
	T ₂	2	3	5	1	3	5			
	T ₃	0	6	5	0	6	3			
	Total				2	9	9	1	5	2

Banker's Algorithm: Example

Q1: How many resources of type A, B, and C are there overall?

		RESOURCES								
		MAX			ALLOCATION			AVAILABLE		
		A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1			
	T ₁	1	7	5	1	0	0			
	T ₂	2	3	5	1	3	5			
	T ₃	0	6	5	0	6	3			
	Total				2	9	9	1	5	2

$$\begin{aligned}
 A &= 2 + 1 = 3 \\
 B &= 9 + 5 = 14 \\
 C &= 9 + 2 = 11
 \end{aligned}$$

Banker's Algorithm: Example

Q2: What is the content of the NEED matrix?

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1						
	T ₁	1	7	5	1	0	0						
	T ₂	2	3	5	1	3	5						
	T ₃	0	6	5	0	6	3						
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

Q2: What is the content of the NEED matrix?

$$NEED[i, j] = MAX[i, j] - ALLOCATION[i, j]$$

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1						
	T ₁	1	7	5	1	0	0						
	T ₂	2	3	5	1	3	5						
	T ₃	0	6	5	0	6	3						
	Total				2	9	9	1	5	2			

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$$NEED[i, j] = MAX[i, j] - ALLOCATION[i, j]$$

		RESOURCES									NEED		
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0-0 = 0		
	T ₁	1	7	5	1	0	0						
	T ₂	2	3	5	1	3	5						
	T ₃	0	6	5	0	6	3						
Total					2	9	9	1	5	2			

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$$NEED[i, j] = MAX[i, j] - ALLOCATION[i, j]$$

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	$0-0=0$	
	T ₁	1	7	5	1	0	0						
	T ₂	2	3	5	1	3	5						
	T ₃	0	6	5	0	6	3						
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

Q2: What is the content of the NEED matrix?

$$NEED[i, j] = MAX[i, j] - ALLOCATION[i, j]$$

		RESOURCES									NEED		
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	1-1 = 0
	T ₁	1	7	5	1	0	0						
	T ₂	2	3	5	1	3	5						
	T ₃	0	6	5	0	6	3						
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

Q2: What is the content of the NEED matrix? $NEED[i, j] = MAX[i, j] - ALLOCATION[i, j]$

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

Q3: Is the system in a safe state? Why?

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

Let's start with T_0

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

Eventually, T_0 finishes and releases all its resources

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

T_1 can't execute as it still might NEED (0, 7, 5) and AVAILABLE = (1, 5, 3)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	8	1	5	3			

Banker's Algorithm: Example

T_2 can execute as it still might NEED (1, 0, 0) and **AVAILABLE** = (1, 5, 3)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	8	1	5	3			

Banker's Algorithm: Example

T_2 can execute as it still might NEED (1, 0, 0) and **AVAILABLE** = (1, 5, 3)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	2	3	5				0	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				3	9	8	0	5	3			

Banker's Algorithm: Example

T_2 eventually finishes and releases all its resources

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	0	6	3				0	0	2
	Total				1	6	3	2			8	8	

Banker's Algorithm: Example

T_3 can execute as it still might NEED (0, 0, 2) and **AVAILABLE** = (2, 8, 8)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	0	6	3				0	0	2
	Total				1	6	3	2	8	8			

Banker's Algorithm: Example

T_3 can execute as it still might NEED (0, 0, 2) and **AVAILABLE** = (2, 3, 6)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	0	6	5				0	0	0
	Total				1	6	5	2	8	6			

Banker's Algorithm: Example

T_3 eventually finishes and releases all its resources

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	-	-	-				-	-	-
	Total				1	0	0	2	14	11			

Banker's Algorithm: Example

T_1 can now execute since NEED (0, 7, 5) and AVAILABLE = (2, 14, 11)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	7	5				0	0	0
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	-	-	-				-	-	-
	Total				1	7	5	2					

Banker's Algorithm: Example

We have found a sequence of execution T_0, T_2, T_3, T_1 which leads to safe state!

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	-	-	-				-	-	-
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	-	-	-				-	-	-
	Total				-	-	-	3	14	11			

Banker's Algorithm: Example

Q4: If T_1 issues a REQUEST (0, 5, 2), can this be granted immediately?

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

We have to ask ourselves: 1. if the request can be satisfied;
2. if it will lead to a safe state

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

To answer 1. check if: a. REQUEST \leq NEED and b. REQUEST \leq AVAILABLE

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

1.a. REQUEST ≤ NEED?

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

1.a. REQUEST \leq NEED? YES! $(0, 5, 2) \leq (0, 7, 5)$

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

1.b. REQUEST \leq AVAILABLE?

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

1.b. REQUEST \leq AVAILABLE? YES! $(0, 5, 2) \leq (1, 5, 2)$

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

To answer **2.** we simulate the request is granted and see if we are still in a safe state

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	0	0				0	7	5
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	9	9	1	5	2			

Banker's Algorithm: Example

To answer **2.** we simulate the request is granted and see if we are still in a safe state

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	14	11	1	0	0			

Banker's Algorithm: Example

Let's start with T_0

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1				0	0	0
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	14	11	1	0	0			

Banker's Algorithm: Example

Eventually, T_0 finishes and releases all its resources

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	14	10	1	0	1			

Banker's Algorithm: Example

T_1 can't execute as it still might NEED (0, 2, 3) and AVAILABLE = (1, 0, 1)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	14	10	1	0	1			

Banker's Algorithm: Example

T_2 can execute as it still might NEED (1, 0, 0) and **AVAILABLE** = (1, 0, 1)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	1	3	5				1	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				2	14	10	1	0	1			

Banker's Algorithm: Example

T_2 can execute as it still might NEED (1, 0, 0) and **AVAILABLE** = (1, 0, 1)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	2	3	5				0	0	0
	T ₃	0	6	5	0	6	3				0	0	2
	Total				3	14	10	0	0	1			

Banker's Algorithm: Example

T_2 eventually finishes and releases all its resources

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	0	6	3				0	0	2
	Total				1	11	5	2			3	6	

Banker's Algorithm: Example

T_3 can execute as it still might NEED (0, 0, 2) and **AVAILABLE** = (2, 3, 6)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	0	6	3				0	0	2
	Total				1	11	5	2	3	6			

Banker's Algorithm: Example

T_3 can execute as it still might NEED (0, 0, 2) and **AVAILABLE** = (2, 3, 6)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	0	6	5				0	0	0
	Total				1	11	7	2	3	4			

Banker's Algorithm: Example

T_3 eventually finishes and releases all its resources

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	5	2				0	2	3
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	-	-	-				-	-	-
Total					1	5	2	2	9	9			

Banker's Algorithm: Example

T_1 can now execute since NEED (0, 2, 3) and AVAILABLE = (2, 9, 9)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	1	7	5				0	0	0
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	-	-	-				-	-	-
	Total				1	7	5	2	7	6			

Banker's Algorithm: Example

We have found a sequence of execution T_0, T_2, T_3, T_1 which leads to safe state!

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	T ₁	1	7	5	-	-	-				-	-	-
	T ₂	2	3	5	-	-	-				-	-	-
	T ₃	0	6	5	-	-	-				-	-	-
	Total				-	-	-	3	14	11			

Summary

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Summary

- **Deadlock** → a situation in which a set of threads/processes cannot proceed because each one requires resources held by another
- **Detection and Recovery** → recognize deadlock after it has occurred and break it
- **Prevention** → design resource allocation strategies which guarantee at least one of the 4 necessary deadlock conditions never holds
- **Avoidance** → runtime checks to avoid deadlock online

Summary

In practice, most OSs don't do anything and leave it all to applications

