

Sistemi Operativi

Corso di Laurea in Informatica

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Recap from Last Lecture

- Synchronization **primitives**:
 - Locks
 - Semaphores
 - Monitors

Recap from Last Lecture

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

Another Synchronization Problem

- It's lunch time at the Department of Philosophy

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- 5 philosophers sitting at a round table

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- It's lunch time at the Department of Philosophy
- 5 philosophers sitting at a round table
- Each philosopher has one chopstick on her/his left and one on her/his right (i.e., 5 chopsticks in total)
- 2 things philosophers are good at 😊:
 - Eating
 - Thinking

The Dining Philosophers

- Thinking means do nothing (just kidding, but you get the idea!)

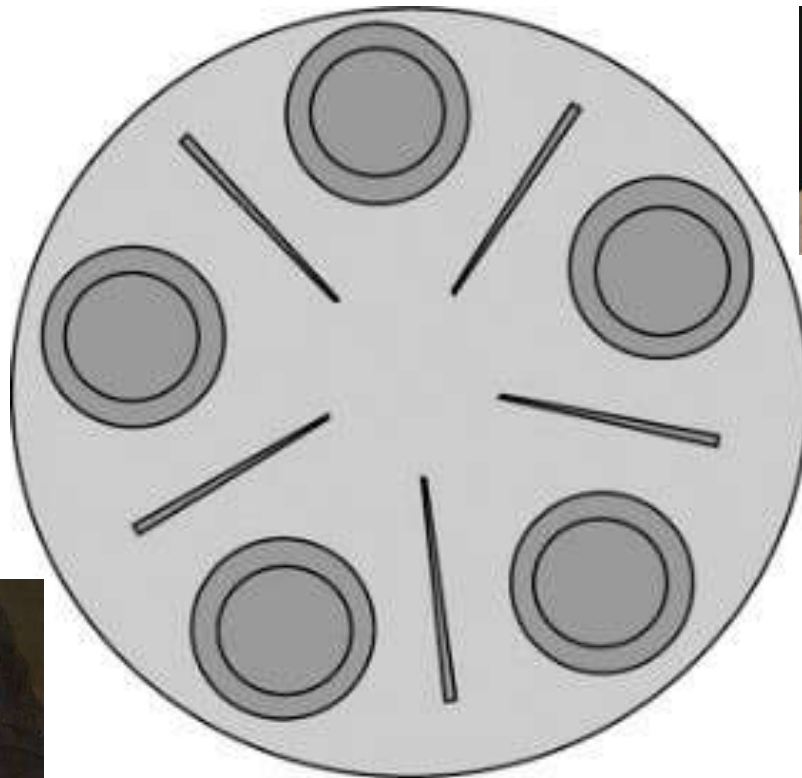
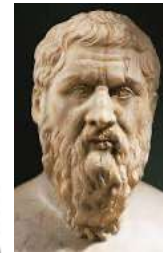
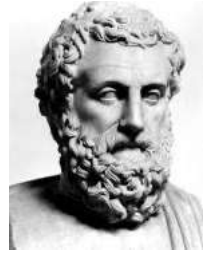
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 - Try to pick up the two closest chopsticks (the left and the right ones)
 - Block if a neighbour has already picked up a chopstick

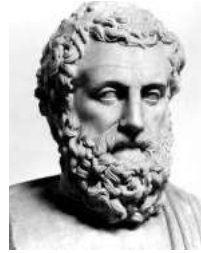
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- Eating means acquiring 2 chopsticks, but how?
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- After eating, put down both chopsticks and go back thinking!

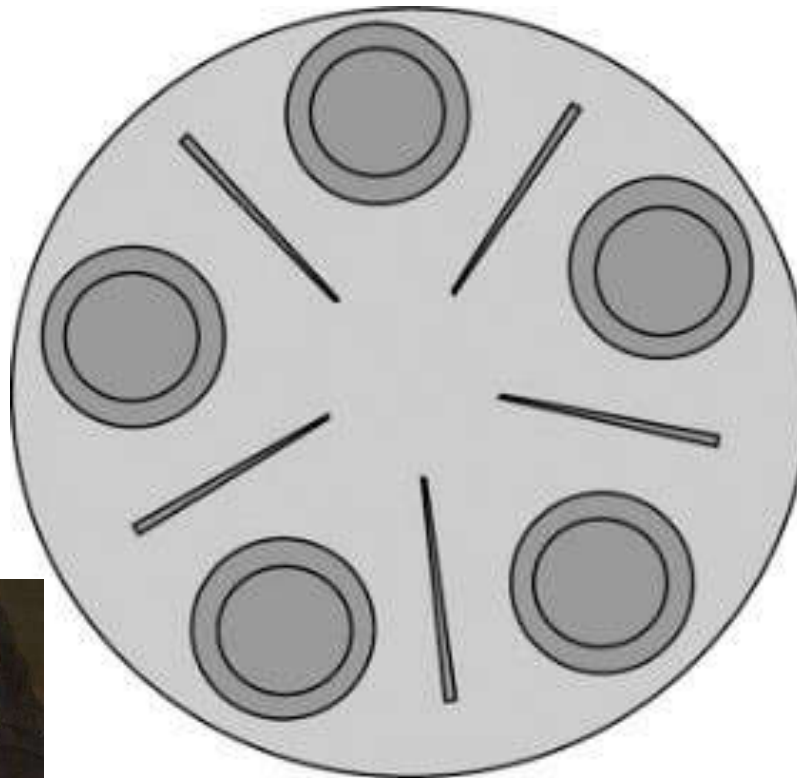
The Dining Philosophers



The Dining Philosophers



How to make them not starving?



The Dining Philosophers

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Very inefficient! Only **one** philosopher at a time can eat

We still want some concurrency here 😊

The Dining Philosophers: Solution I

```
Semaphore chopsticks[5];

while(True) {
    chopsticks[(i-1)%5].wait(); // wait on the left chopstick
    chopsticks[(i+1)%5].wait(); // wait on the right chopstick

    eat();

    chopsticks[(i-1)%5].signal(); // signal on the left chopstick
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}
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Is this solution correct?

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Is this solution correct?

No! Possible **deadlock** if all philosophers take the left chopstick

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Testing if either one of the two neighbours of a given philosopher is currently eating (condition variables)

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Idea: Before picking one chopstick be sure also the second one is available, otherwise wait for the neighbour to finish

Testing if either one of the two neighbours of a given philosopher is currently eating (condition variables)

Never gonna pick a single chopstick!

The Dining Philosophers: Solution II (monitors)

```
class Philosopher {
    enum Status {
        THINKING,
        HUNGRY,
        EATING
    }
    Status state;

    public Philosopher() {
        this.state = THINKING;
    }
}
```

```
class DiningPhilosophers {
    Philosopher[5] philosophers;

    public DiningPhilosophers() {
        for(int i=0; i < 5; ++i) {
            this.philosophers[i] = new Philosopher();
        }
    }
    // continue implementation ----->
```

```
void canEat(int i) {
    State state = this.philosophers[i].state;
    State left = this.philosophers[(i-1)%5].state;
    State right = this.philosophers[(i+1)%5].state;
    if(left != EATING && right != EATING && state == HUNGRY) {
        state = EATING;
        this.philosophers[i].notify();
    }
}
```

```
void synchronized pickup(int i) {
    this.philosophers[i].state = HUNGRY;
    canEat(i);
    if(this.philosophers[i].state != EATING) {
        this.philosophers[i].wait();
    }
}
```

```
void synchronized putdown(int i) {
    this.philosophers[i].state = THINKING;
    canEat((i - 1) % 5); // left neighbour
    canEat((i + 1) % 5); // right neighbour
}
```


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Real-World Examples

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 - Producer-Consumer
 - Audio/Video player embedded in a web browser: shared data buffer + network and render threads
 - Reader-Writer
 - Banking system: read vs. update account balances
 - Dining Philosophers
 - Lock on multiple resources: e.g., travel reservation (hotel, airline, car rental databases)

Our Journey

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

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printer.wait();  
disk.wait();
```

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

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

A starts first



Thread **B**

```
disk.wait();  
printer.wait();
```

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

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

What is Deadlock?

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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**

```
disk.wait();  
printer.wait();
```

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

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

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Thread A

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

B takes over



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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Thread **A**

```
printer.wait();  A executes again and blocks  
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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disk.signal();
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Thread **B**

```
disk.wait();  
printer.wait();
```

B executes again and blocks



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

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

A waits **B** to release the **disk**

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Thread **B**

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printer.wait();
```

```
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```
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B waits **A** to release the **printer**

Deadlock: Terminology

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

Deadlock vs. Starvation

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- 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

- Deadlock *can* happen if *all* the **4 conditions** below hold

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 - **Circular Wait** → a set of waiting threads t_1, \dots, t_n where t_i is waiting on $t_{(i+1)\%n}$

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- Edges can be of **2 types**:

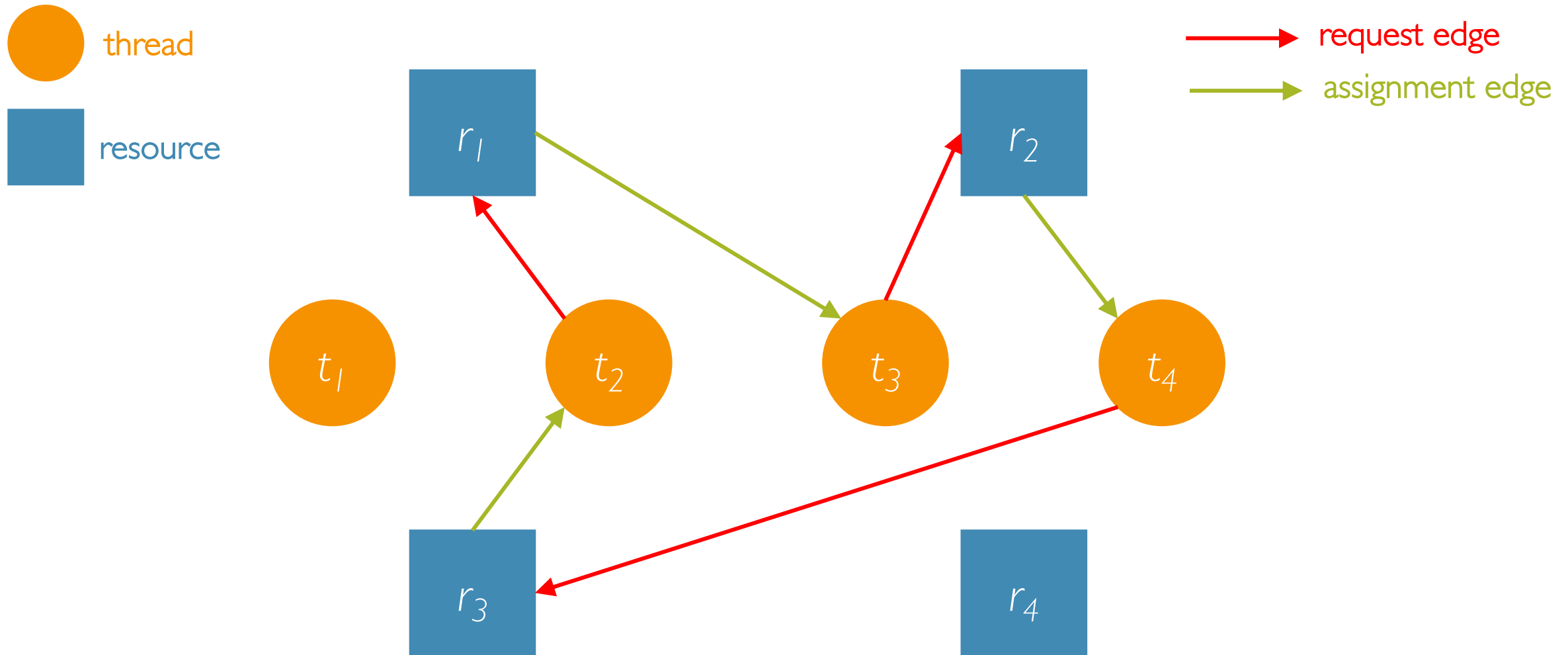
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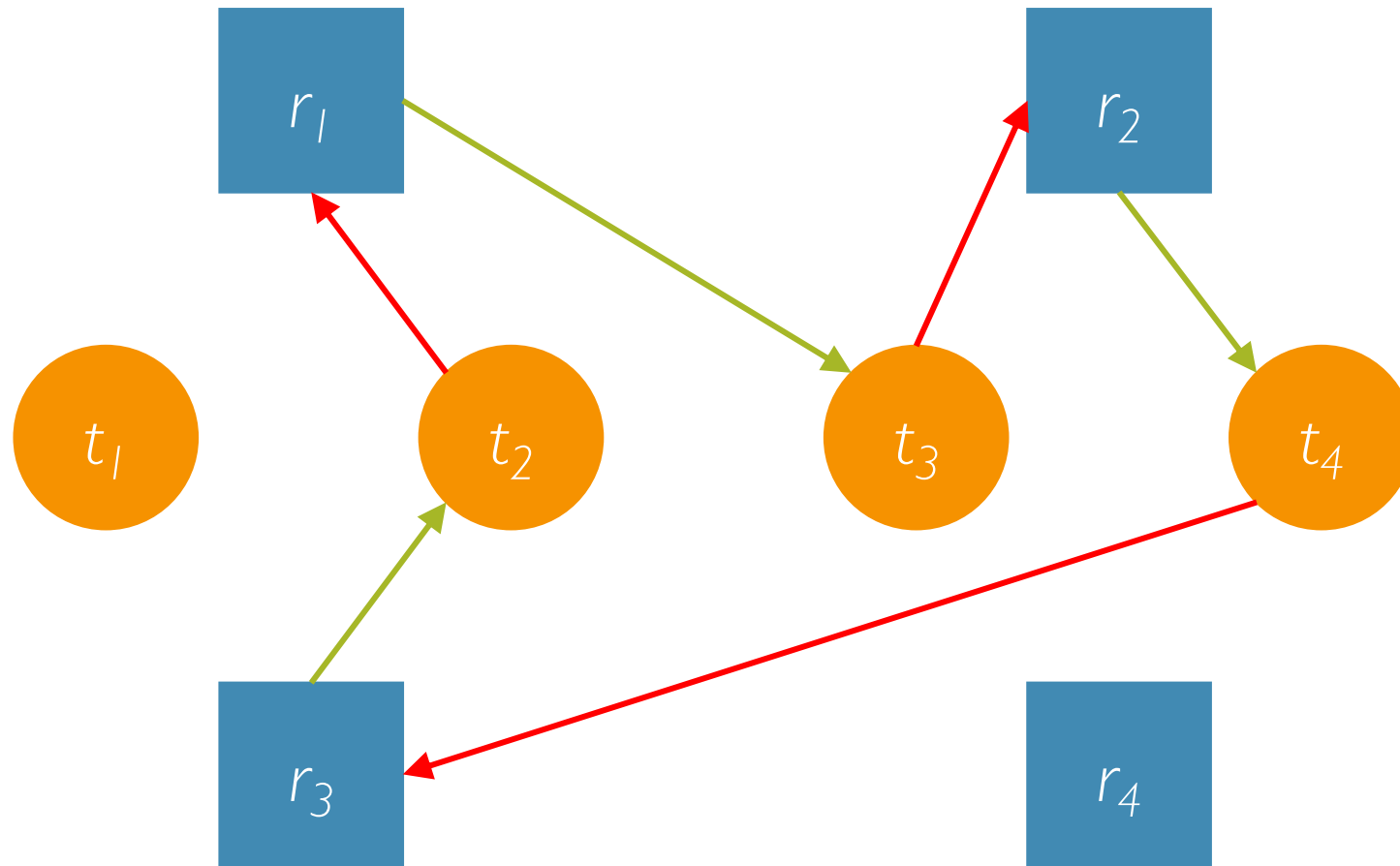
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 - **Assignment Edge** \rightarrow a directed edge (r_j, t_i) indicates that the OS has allocated r_j to t_i

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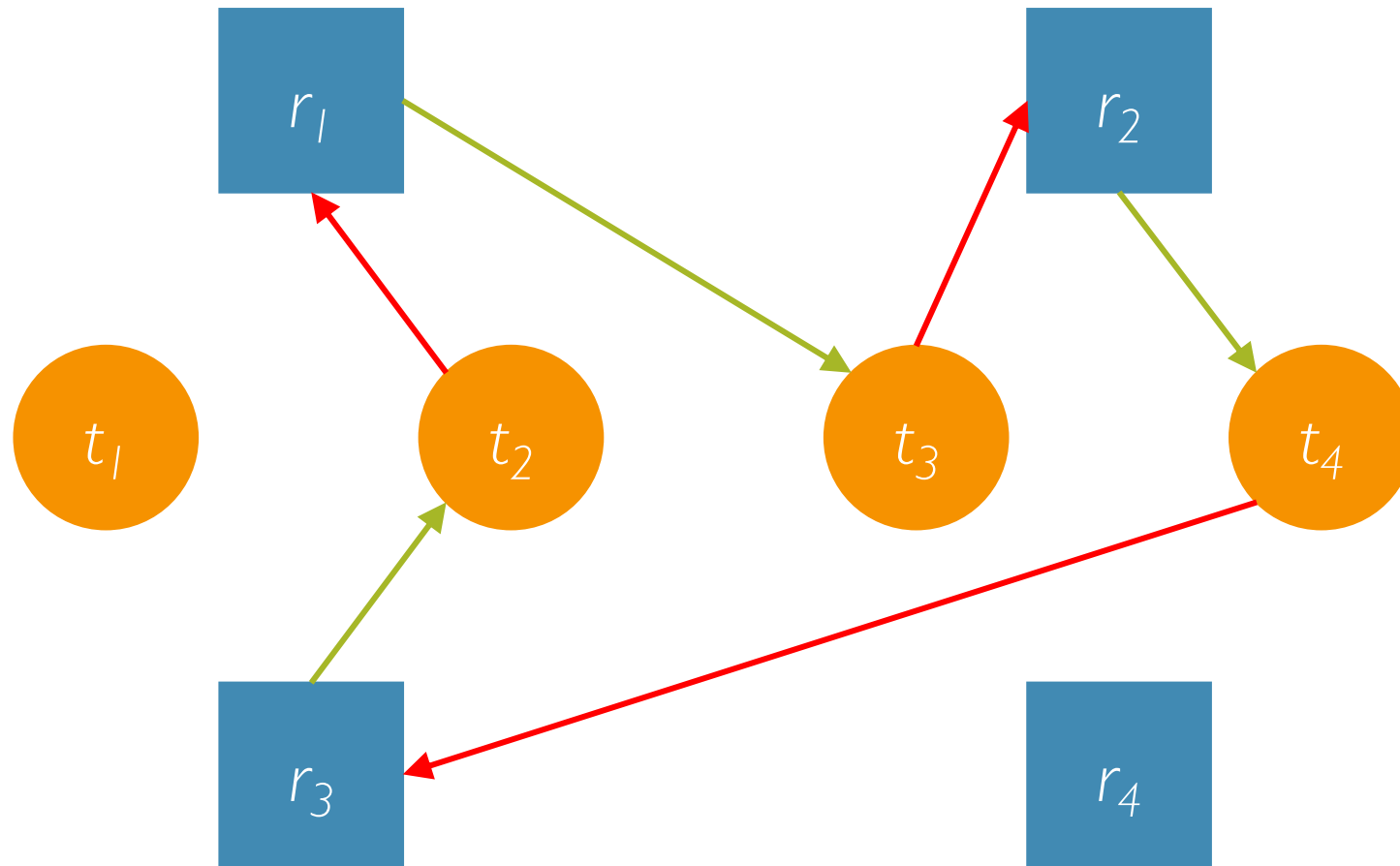


Deadlock Detection: Resource Allocation Graph



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

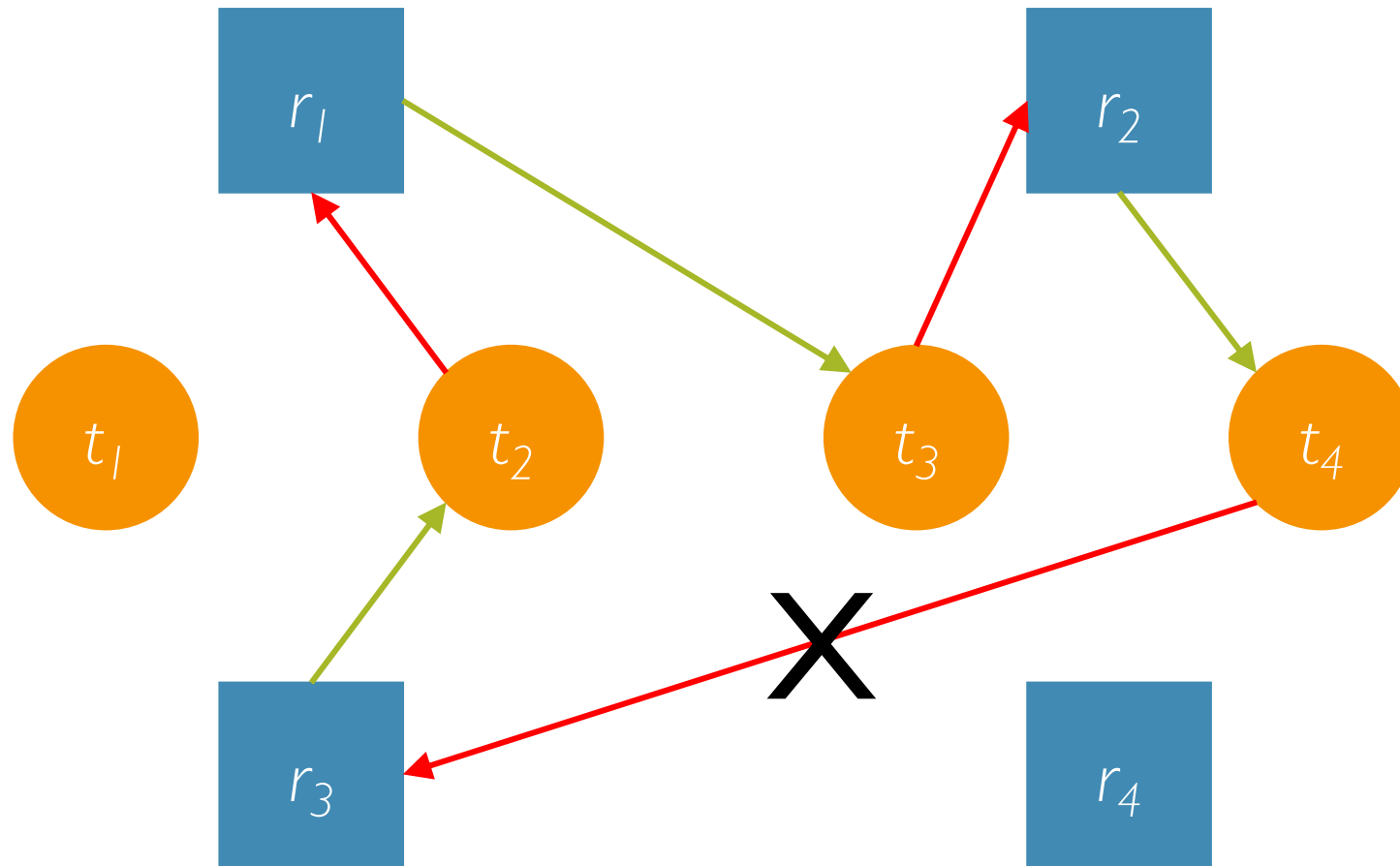
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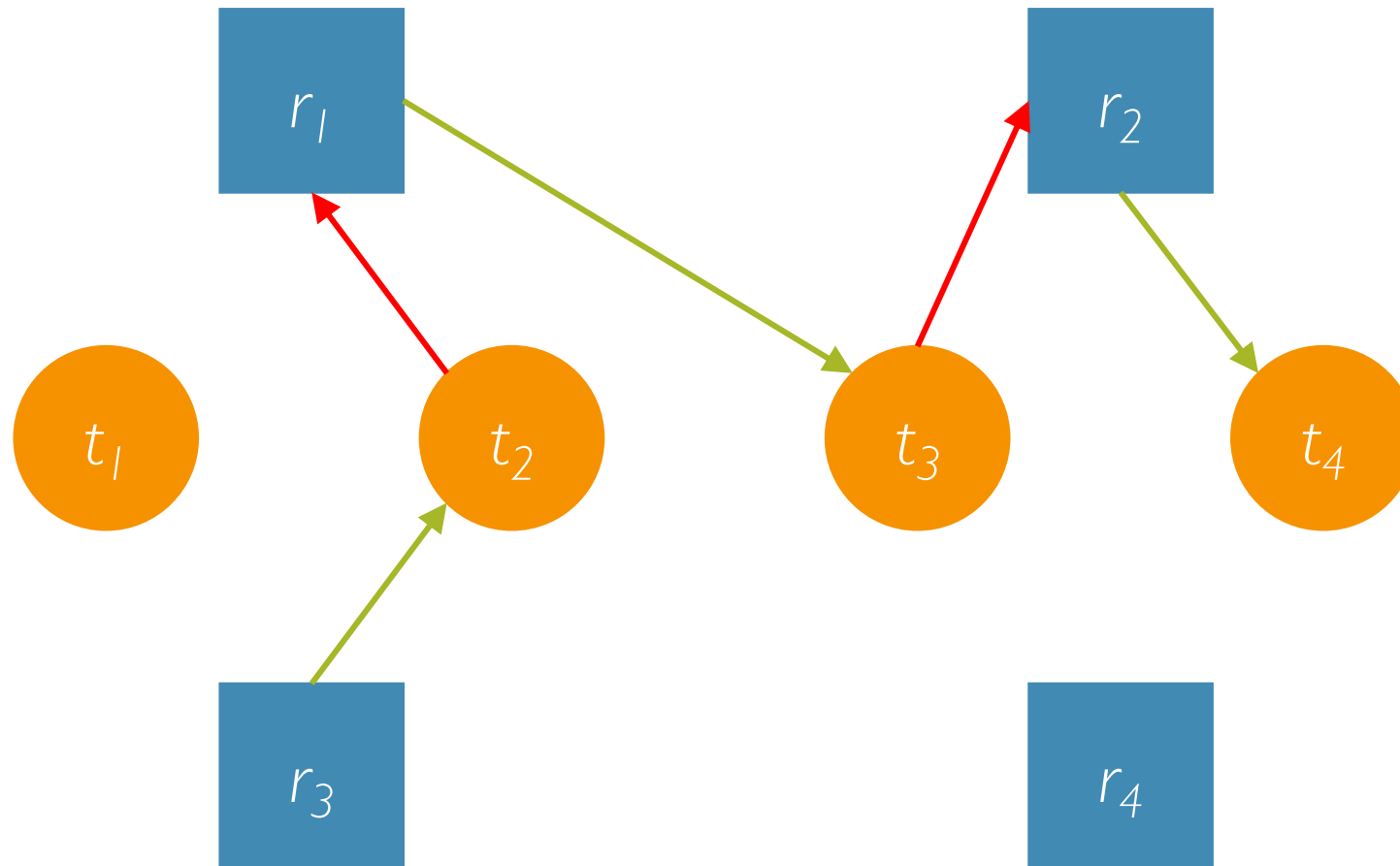
Why?

Deadlock Detection: Resource Allocation Graph



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

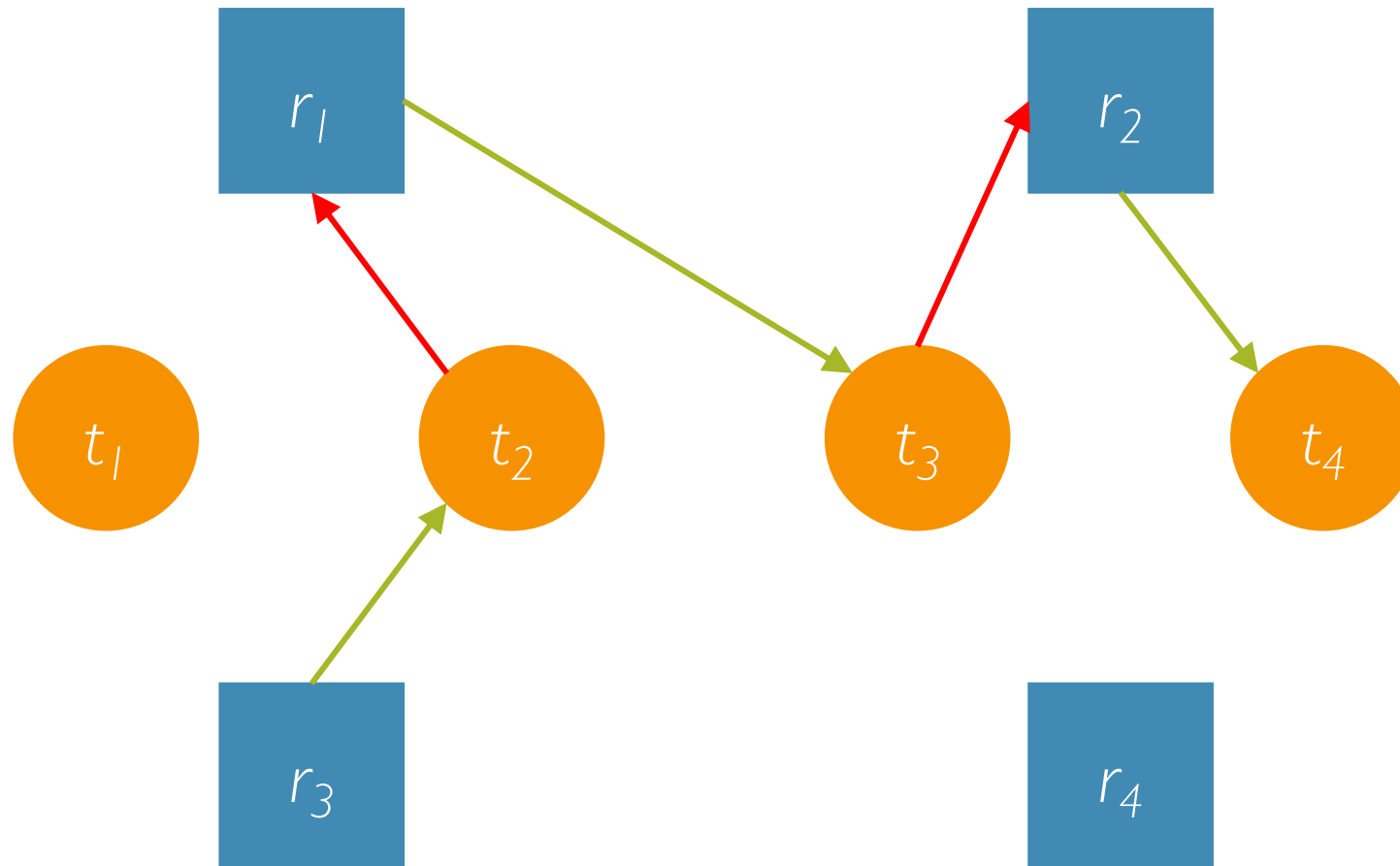
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Suppose we remove the edge (t_4, r_3) so as to remove the cycle

No deadlock can occur as t_4 is not waiting on anything...

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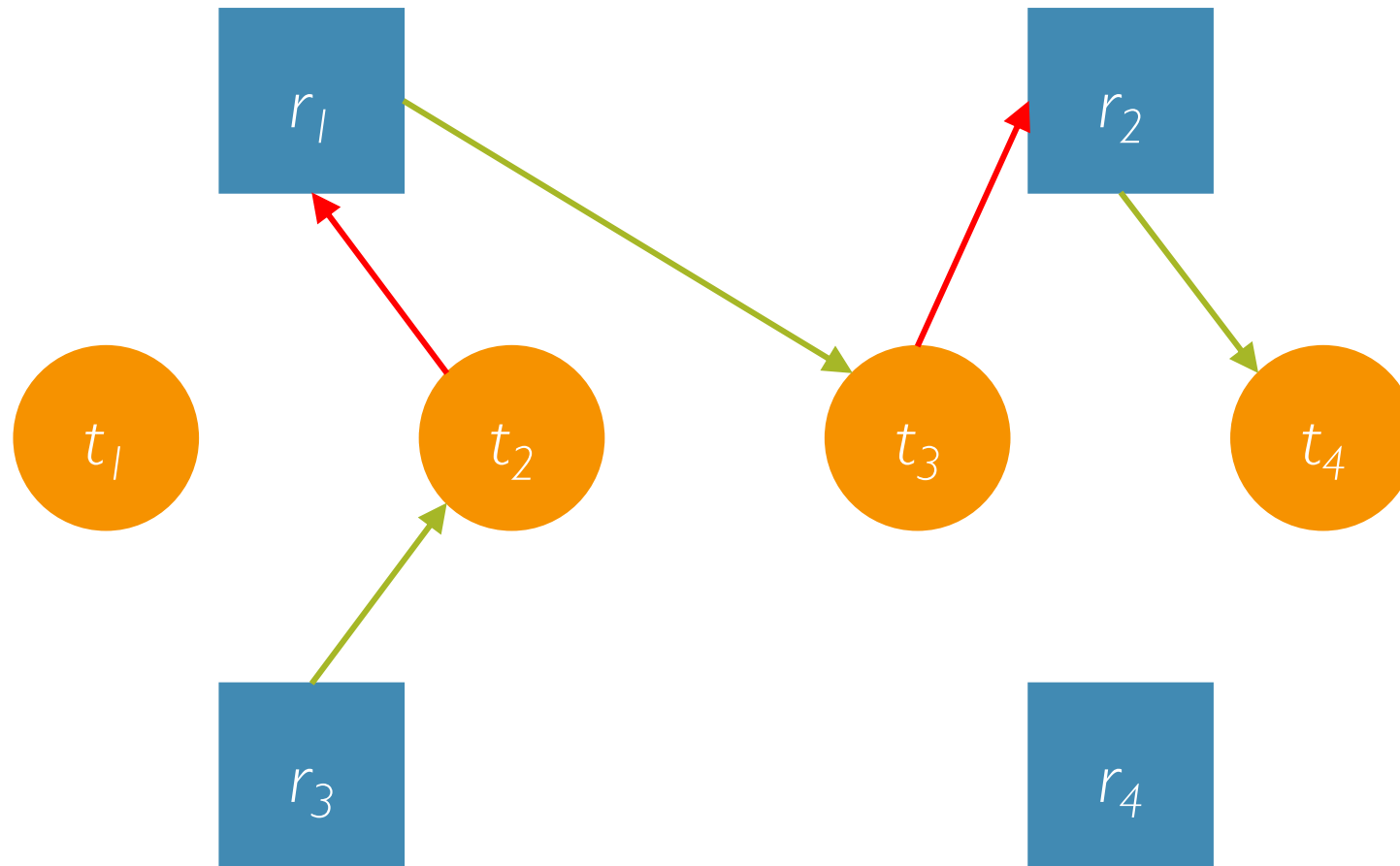


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Therefore, t_4 can run and eventually will release r_2 , which wakes up t_3

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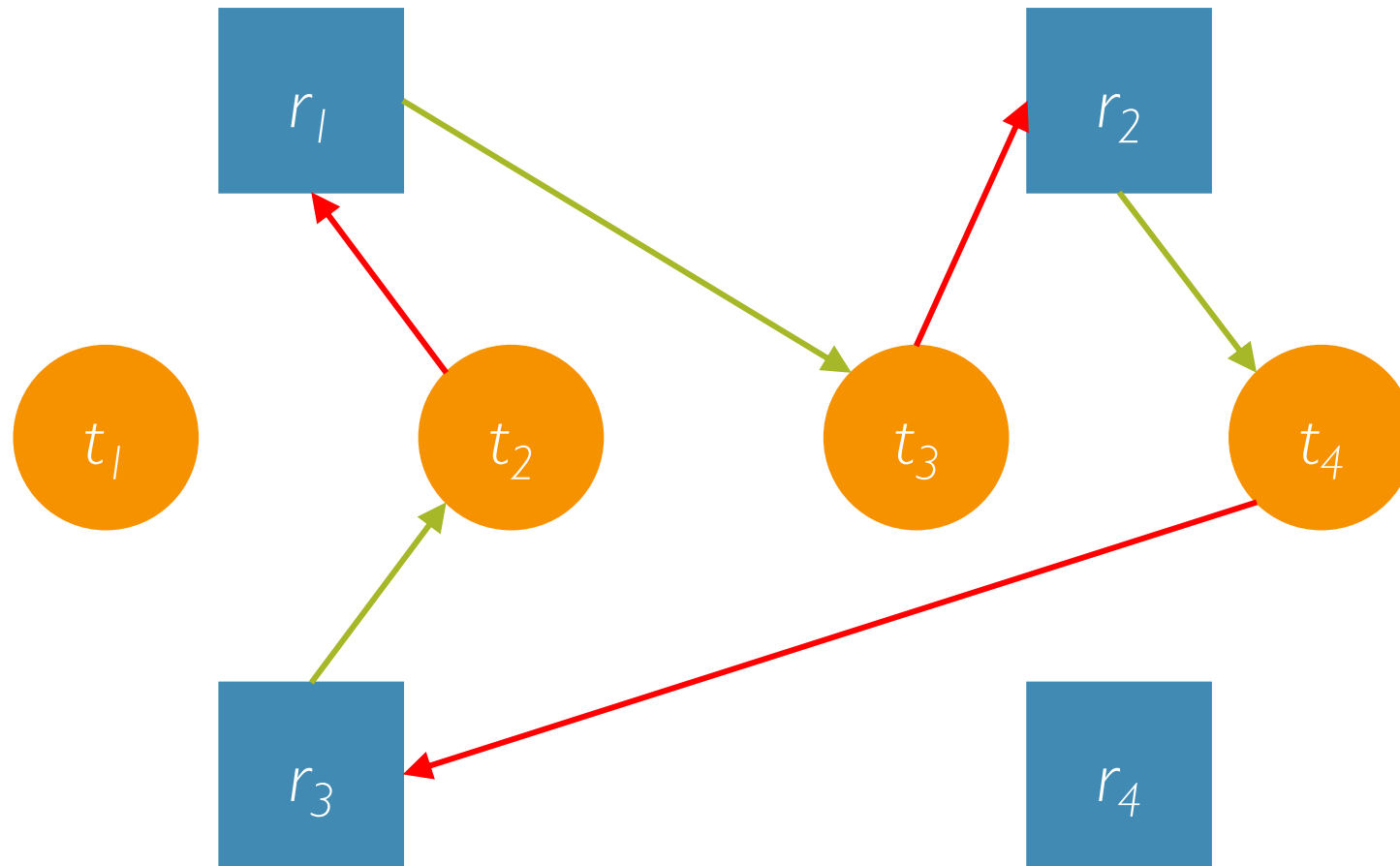
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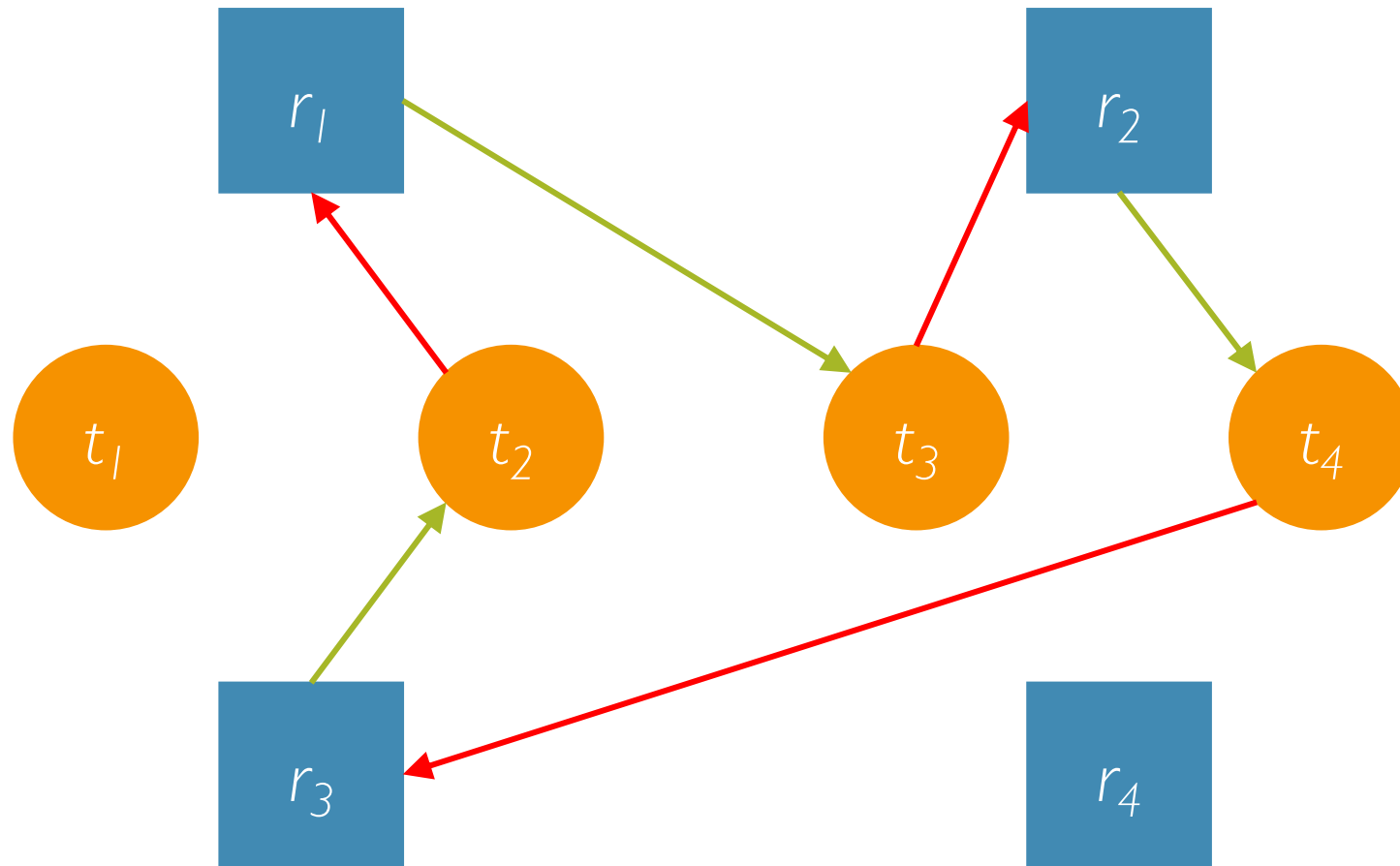
And so on and so forth...

Deadlock Detection: Resource Allocation Graph



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

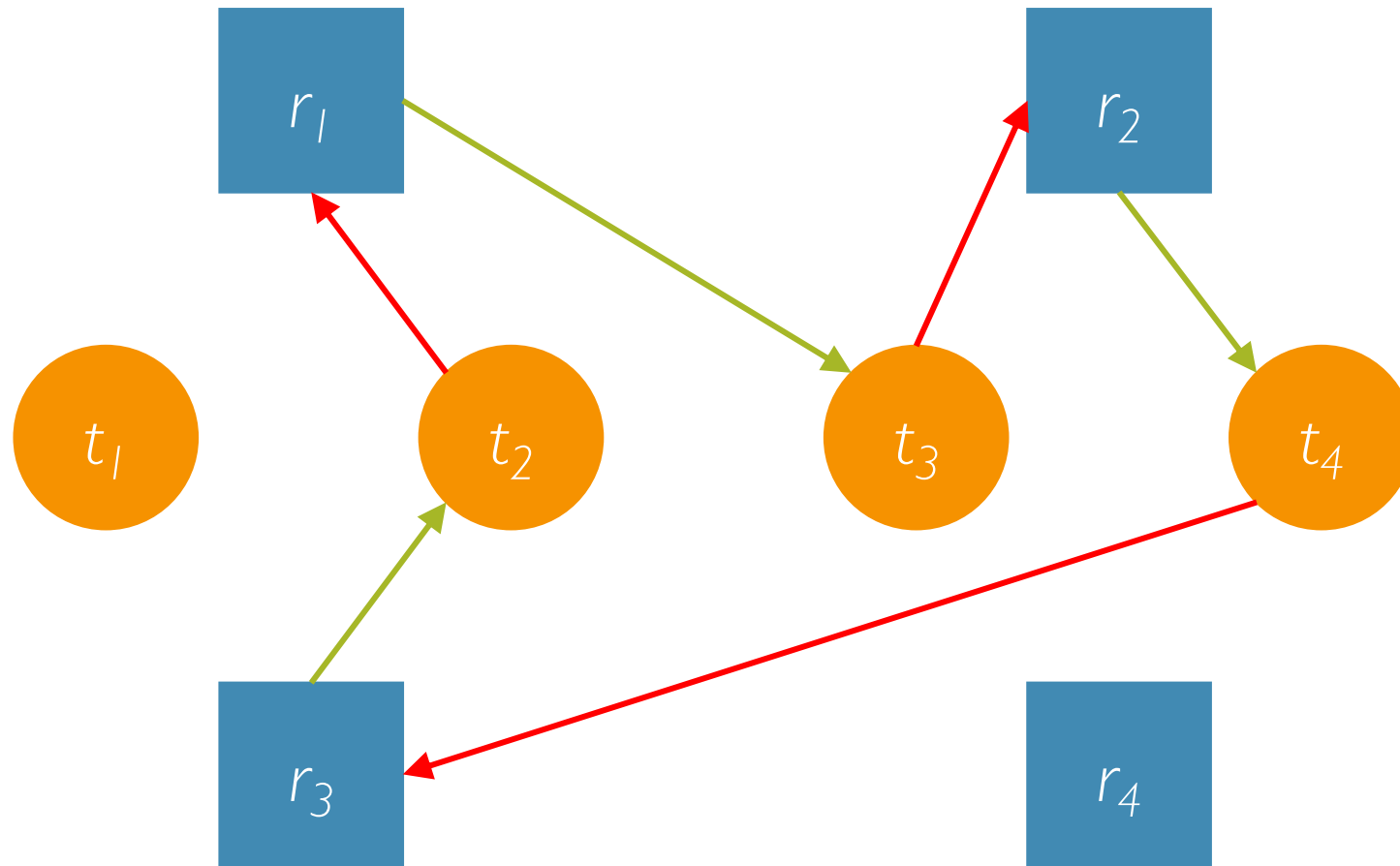
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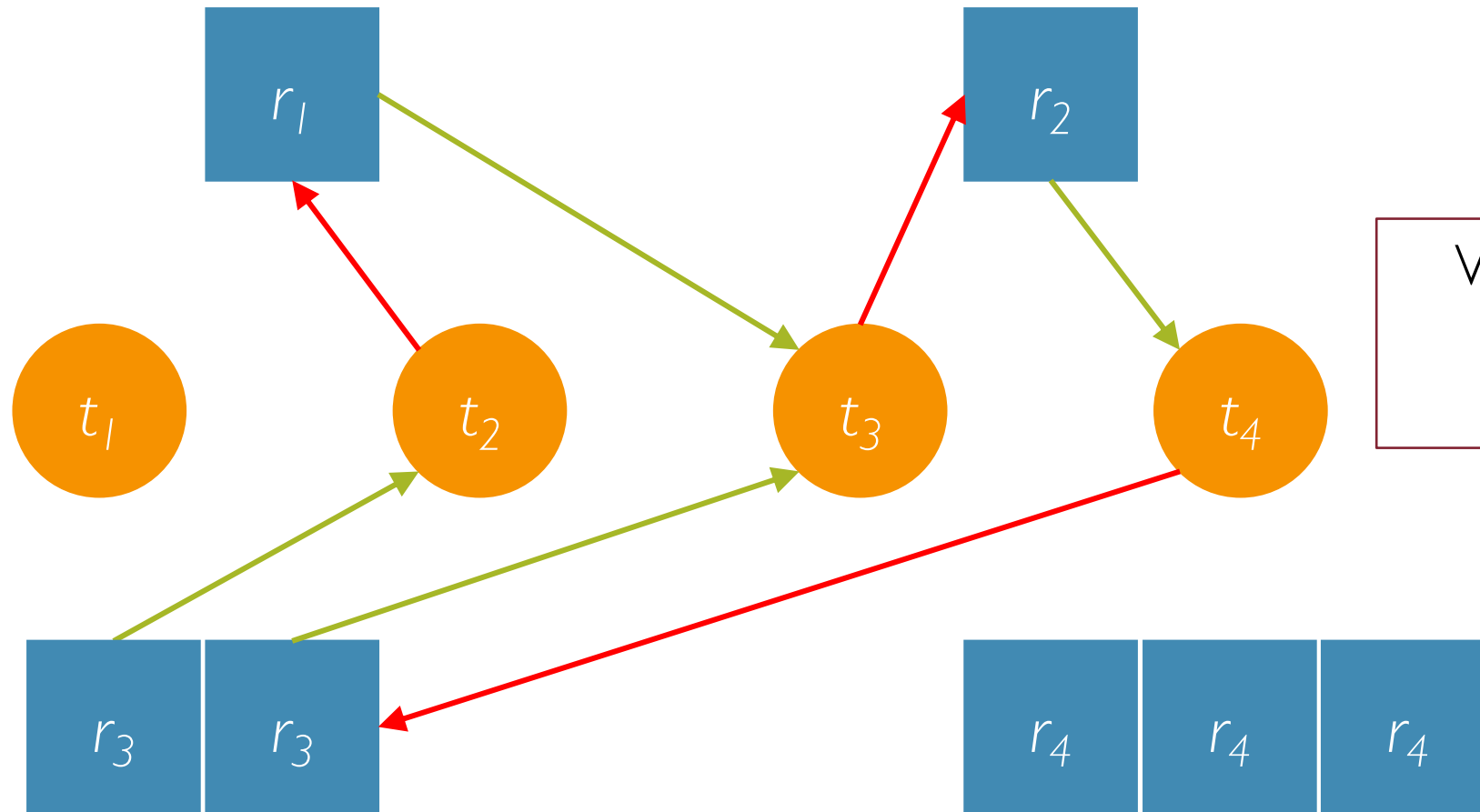
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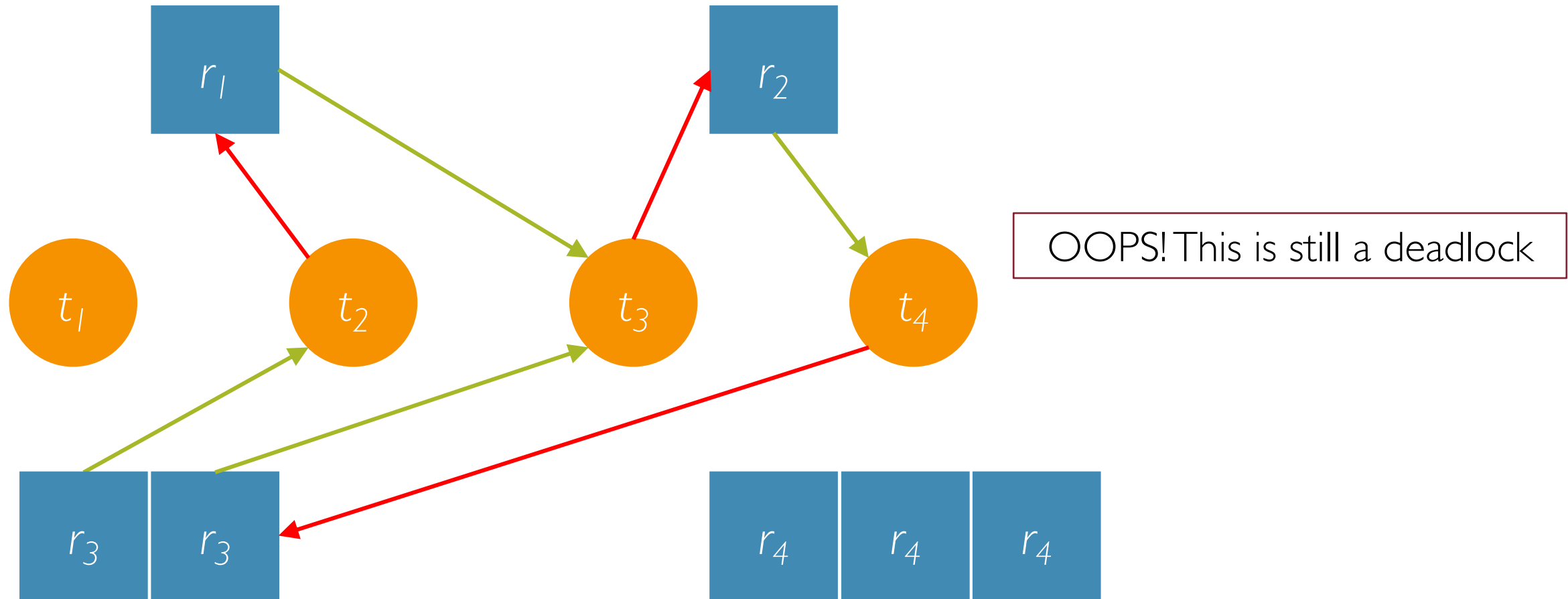
We are implicitly assuming the **multiplicity** of each resource is 1 (i.e., we have one r_1 , one r_2 , etc.)

Deadlock Detection: Resource Allocation Graph

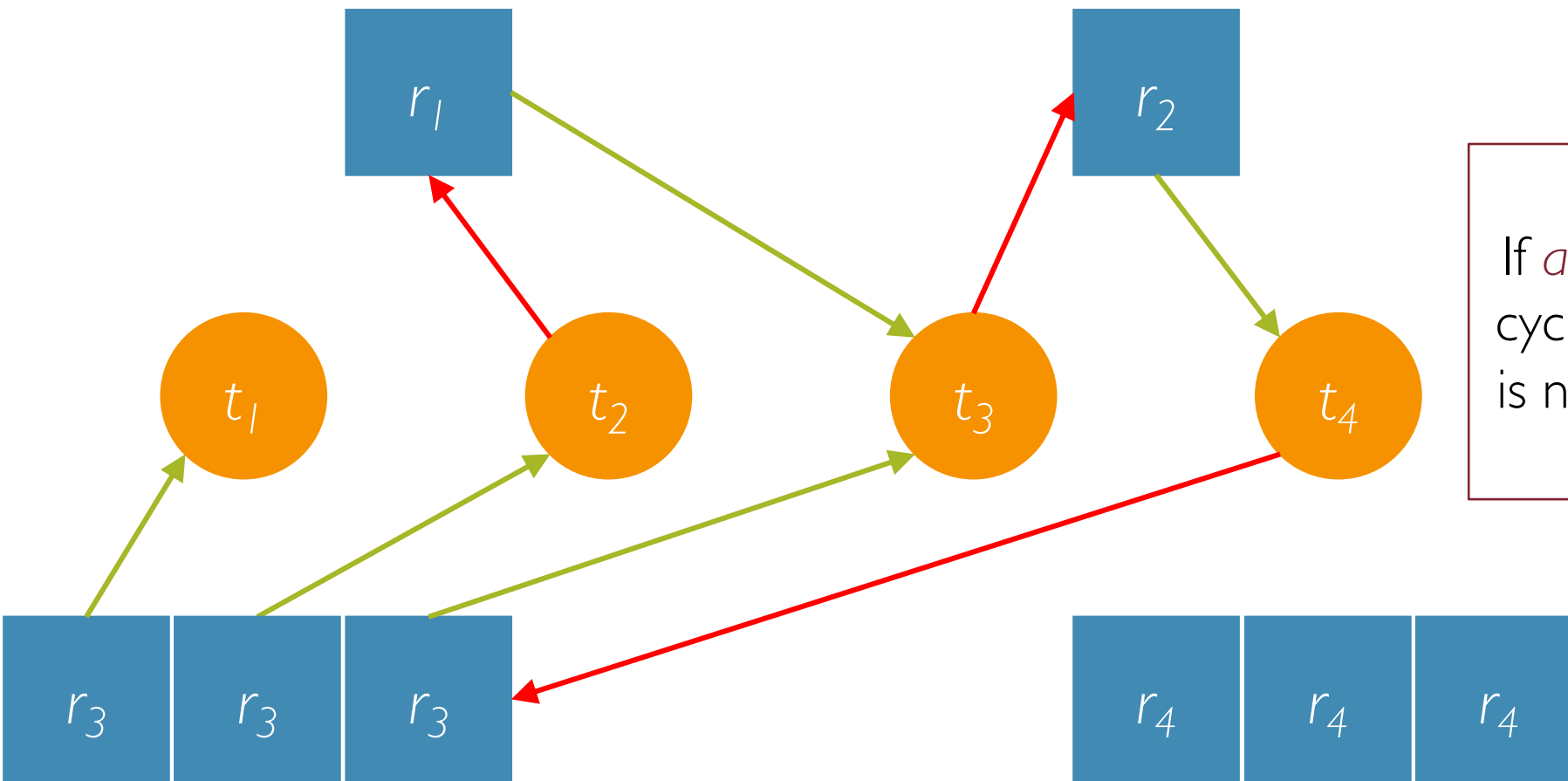


What if there are **multiple** instances of the same resource?

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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- How? Several ways of doing it:
 - Kill all the threads in the cycle (quite harsh, ugh?)
 - Kill all the threads one at a time, forcing each one of them to release resource(s)
 - Preempt resources one at a time rolling back to a consistent status (e.g., common in database transactions)

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

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- When to run such a detection algorithm?
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- What do modern OSs do? Nothing! They leave it to the programmer!

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Deadlock Prevention

- Ensure that *at least one* of the 4 necessary conditions doesn't hold

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- Ensure that *at least one* of the 4 necessary conditions doesn't hold
 - **Mutual Exclusion** → make resources sharable (though not all can be shared)

Deadlock Prevention

- Ensure that *at least one* of the 4 necessary conditions doesn't hold
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 - Problem: not all resources can be easily preempted (e.g., printers)

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 - Problem: not all resources can be easily preempted (e.g., printers)
 - **Circular Wait** → impose an ordering (i.e., numbering) on resources and enforce to request them in such order

Our Journey

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

Deadlock Avoidance: Resource Reservation

Each thread provides information about the **maximum** number of resources it **might** need during execution

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

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

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

Deadlock Avoidance: Safe State

- A state in which there is a safe sequence for the threads
- An unsafe state does not necessarily mean deadlock (i.e., some threads may not request the maximum number of resources as declared)
- Grant a resource to a thread if the new state is safe, otherwise make it wait even if the resource is available
- This policy ensures no circular-wait condition exists

Deadlock Avoidance: Example

- 3 threads: t_1 , t_2 , and t_3 are competing for 12 tape drives (resources)
- Currently, 11 drives are allocated to the threads, leaving 1 available

Thread	m_i	c_i	$m_i - c_i$
t_1	4	3	1
t_2	8	4	4
t_3	12	4	8

Is the current state safe?

Deadlock Avoidance: Example

Thread	m_i	c_i	$m_i - c_i$
t_1	4	3	1
t_2	8	4	4
t_3	12	4	8

The current state is safe in that there exists a sequence of threads (t_1, t_2, t_3) where each one will get the maximum number of resources without waiting

Deadlock Avoidance: Example

Thread	m_i	c_i	$m_i - c_i$
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t_3	12	4	8

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t_1 can complete using the current allocation and the 1 drive left

Deadlock Avoidance: Example

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t_1 can complete using the current allocation and the **1 drive** left

t_2 can use the current allocation, plus t_1 's resources and **1 drive** left (**4 drives**)

Deadlock Avoidance: Example

Thread	m_i	c_i	$m_i - c_i$
t_1	4	3	1
t_2	8	4	4
t_3	12	4	8

The current state is safe in that there exists a sequence of threads (t_1, t_2, t_3) where each one will get the maximum number of resources without waiting

t_1 can complete using the current allocation and the **1 drive** left

t_2 can use the current allocation, plus t_1 's resources and 1 drive left (**4 drives**)

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
t_3	12	5	7

Suppose t_3 requests one more drive, then now there are **no more available drives**

Theoretically, **everything might still work** (e.g., t_1 may never request another drive)

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

Deadlock Avoidance: Resource Allocation Graph

- An extension of the original definition of resource allocation graph

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- Edges can now be of **3 types**:
 - **Request Edge** \rightarrow a directed edge (t_i, r_j) indicates that t_i has requested r_j , but not yet acquired
 - **Claim (dotted) Edge** \rightarrow a directed edge (t_i, r_j) indicates that t_i might request r_j in the future
 - **Assignment Edge** \rightarrow a directed edge (r_j, t_i) indicates that the OS has allocated r_j to t_i

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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
 - **Assignment Edge** \rightarrow a directed edge (r_j, t_i) indicates that the OS has allocated r_j to t_i
- Satisfying a request means converting a **claim** into an **assignment** edge

Deadlock Avoidance: Resource Allocation Graph

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Deadlock Avoidance: Resource Allocation Graph

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

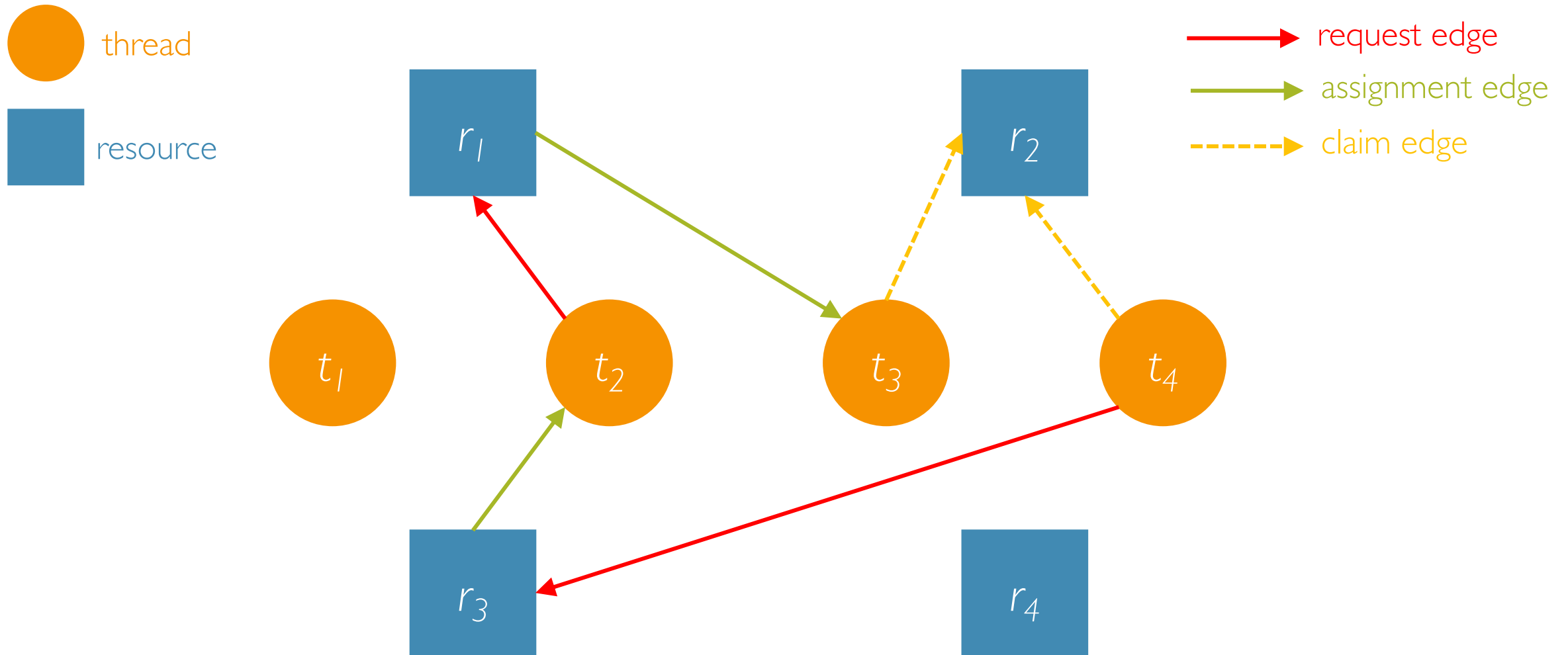
Deadlock Avoidance: Resource Allocation Graph

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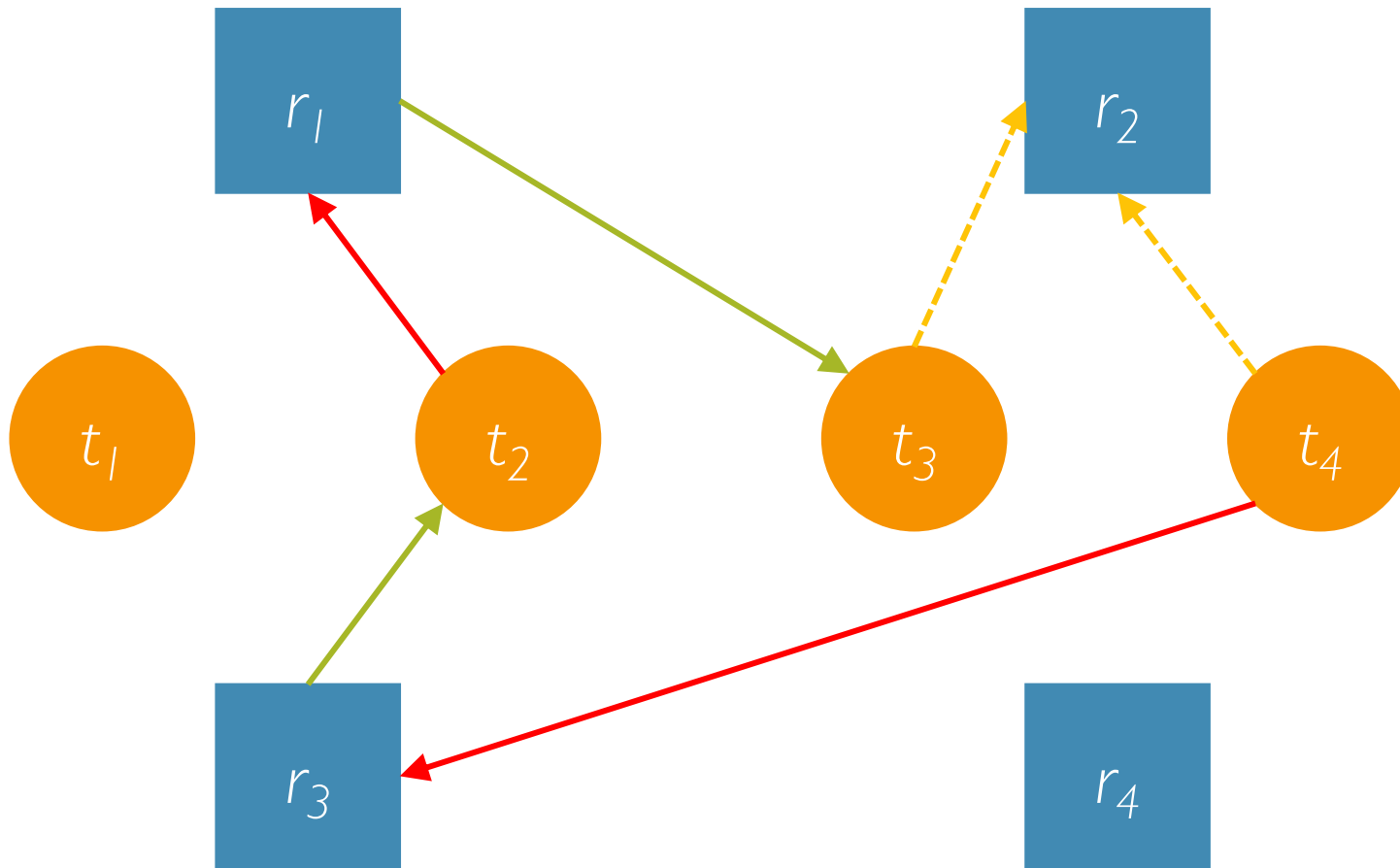
Deadlock Avoidance: Resource Allocation Graph

- 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

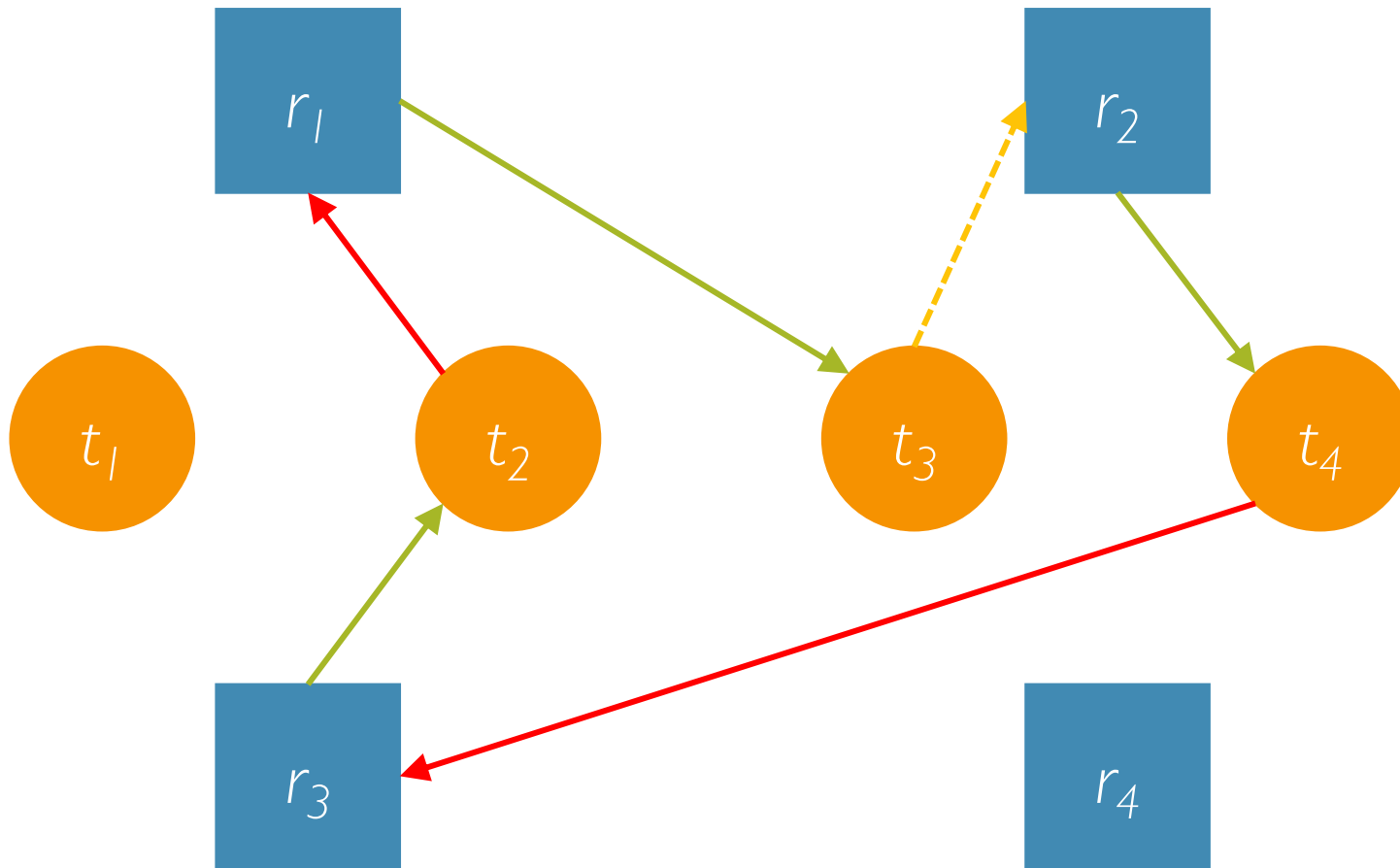


Deadlock Avoidance: Resource Allocation Graph



What happens if t_4 is given r_2 ?

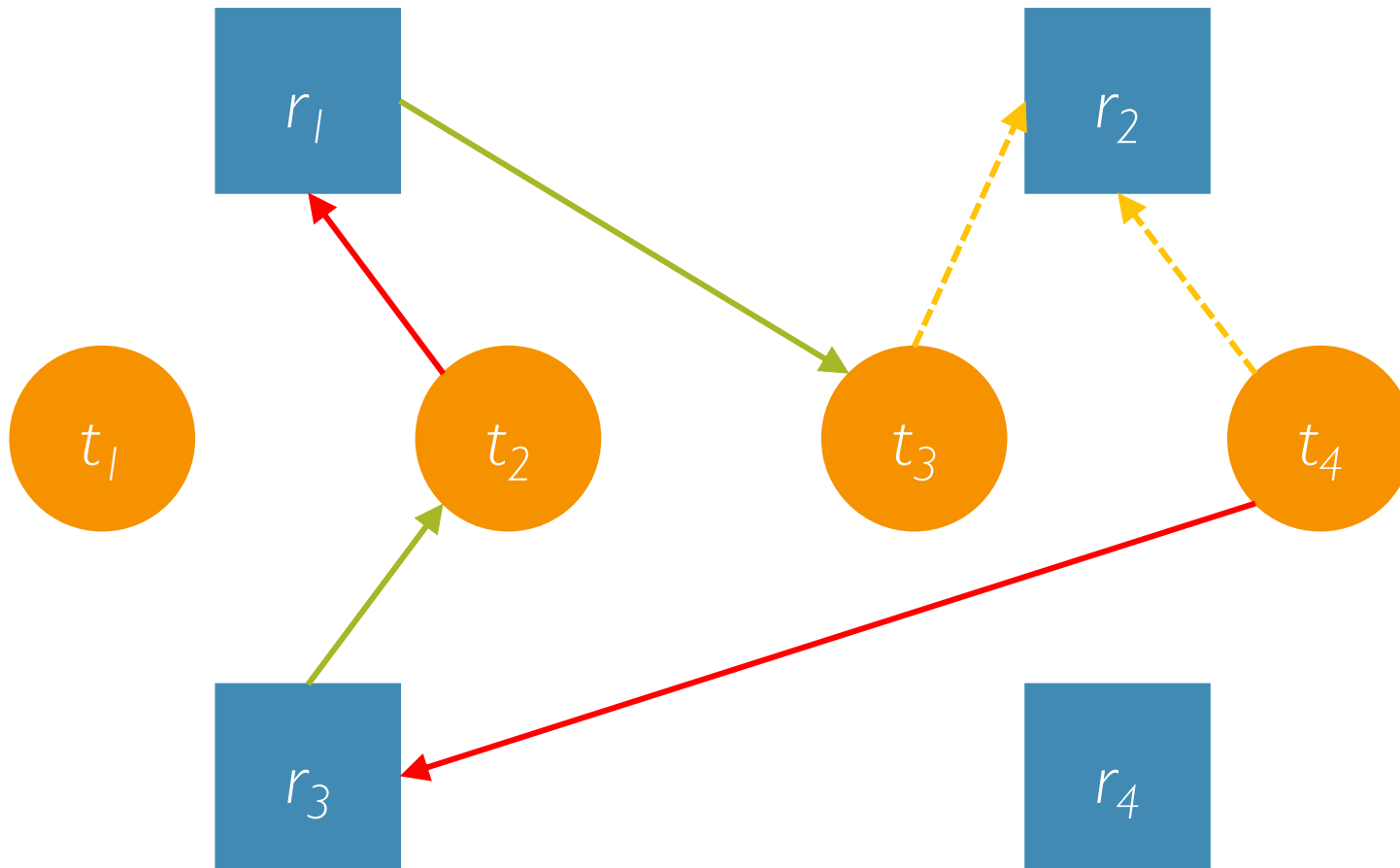
Deadlock Avoidance: Resource Allocation Graph



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

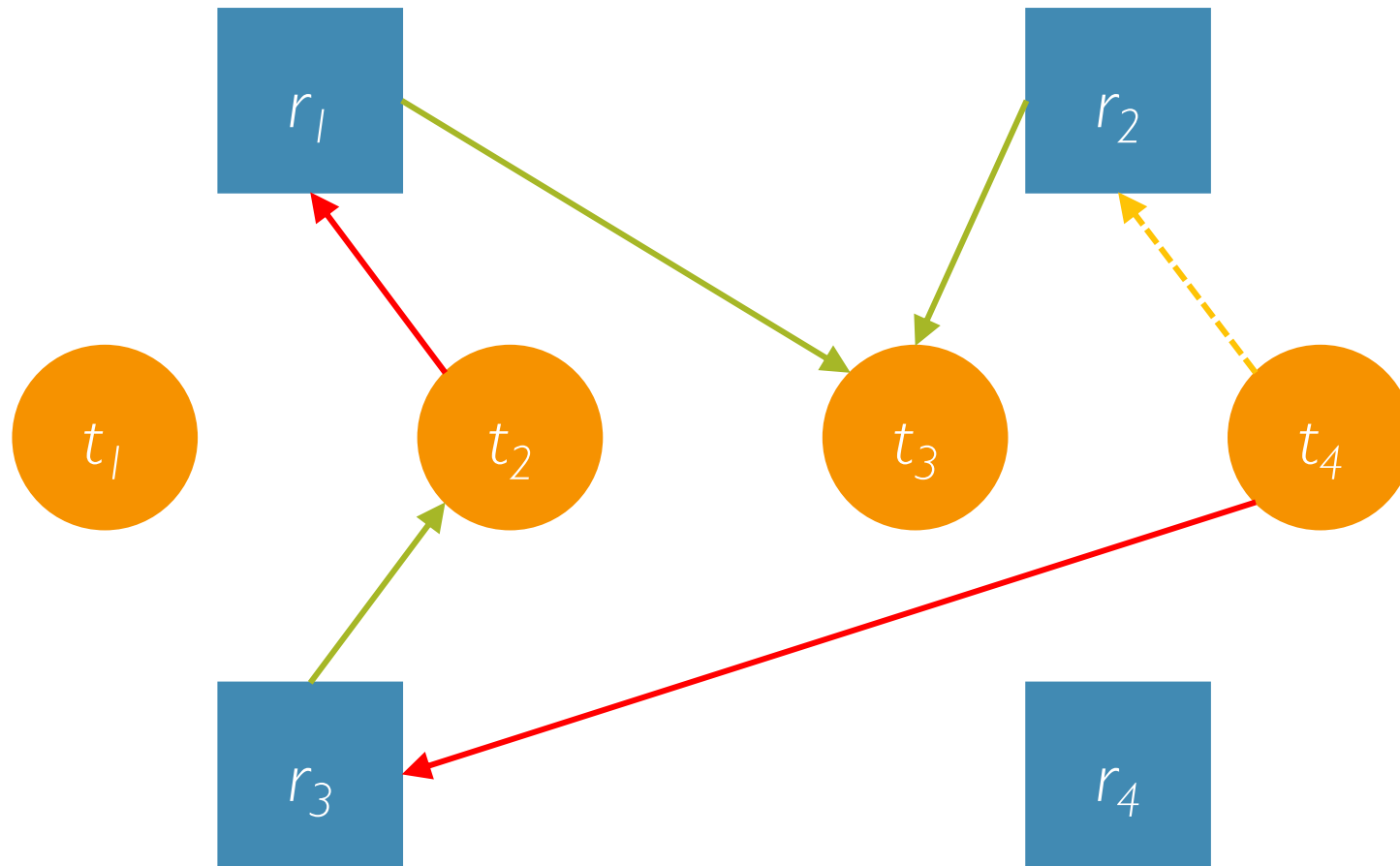
unsafe state

Deadlock Avoidance: Resource Allocation Graph



What happens if t_3 is given r_2 ?

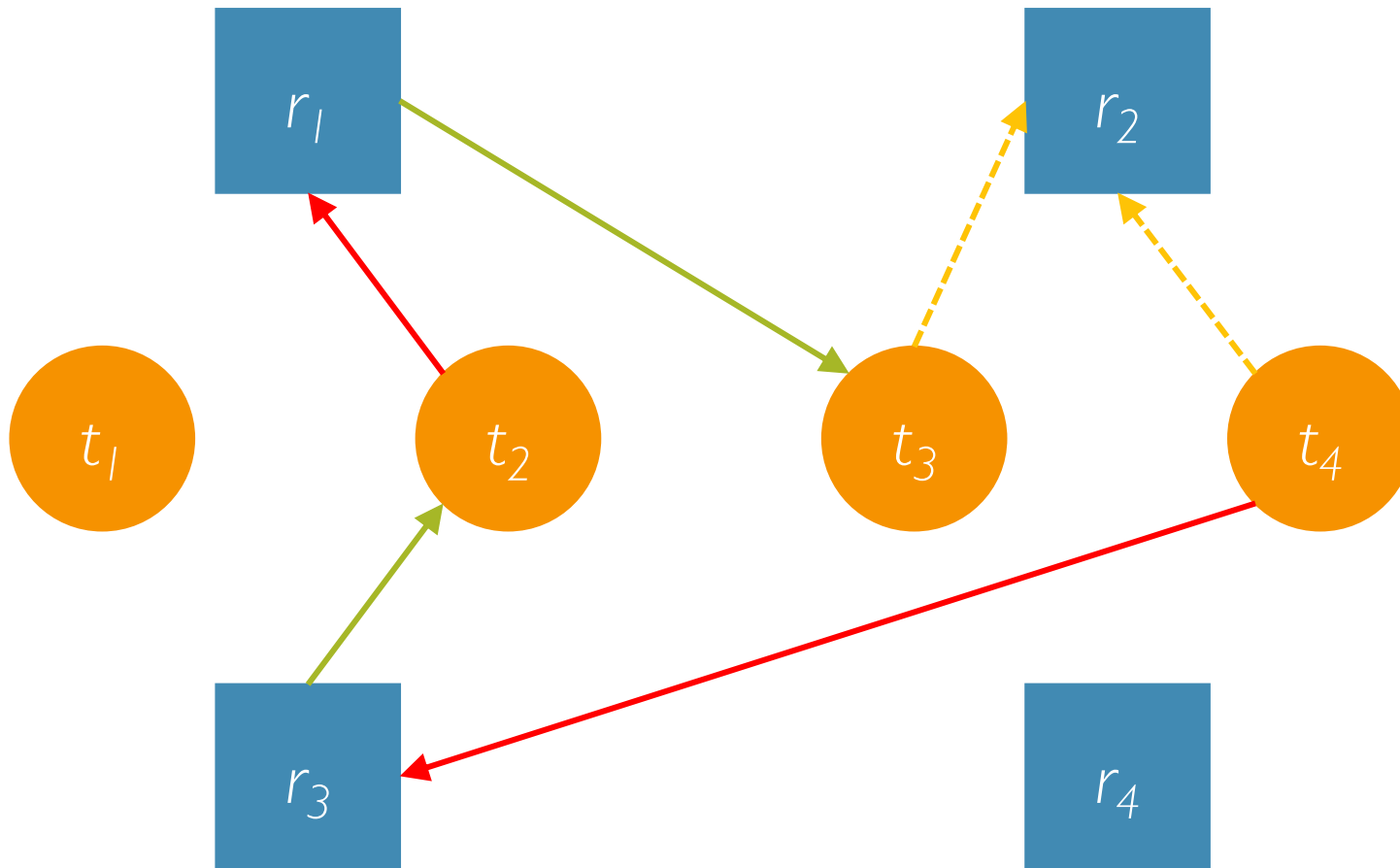
Deadlock Avoidance: Resource Allocation Graph



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

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 - **isSafeState** → given the current status of allocation of resources, tests if this is a safe state
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- 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] ≤ 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 `request > need[i]` raise an error as thread i is attempting to request more resources than it claimed, otherwise go to step 2.
2. If `request > 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

```
available -= request; allocation[i] += request; need[i] -= request;  
isSafeState() ? OK : rollback() and 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			
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	T ₂	2	3	5	1	3	5			
	T ₃	0	6	5	0	6	3			
Total					2	9	9	1	5	2

$A = 2 + 1 = 3$
 $B = 9 + 5 = 14$
 $C = 9 + 2 = 11$

Banker's Algorithm: Example

Q2: What is the content of the NEED matrix?

		RESOURCES									NEED		
		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						
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$$\text{NEED}[i, j] = \text{MAX}[i, j] - \text{ALLOCATION}[i, j]$$

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		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						
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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						
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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						
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	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									NEED		
		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				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									NEED		
		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				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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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	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			

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			
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									NEED		
		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				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 **I.** 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

I.a. REQUEST \leq NEED?

		RESOURCES									NEED		
		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				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

I.a. REQUEST <= NEED?

YES!

(0, 5, 2) <= (0, 7, 5)

		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				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

I.b. REQUEST \leq AVAILABLE?

		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				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

I.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			
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									NEED		
		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				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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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									NEED		
		MAX			ALLOCATION			AVAILABLE					
		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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- **Deadlock** → a situation in which a set of threads/processes cannot proceed because each one requires resources held by another
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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
- In practice, most OSs don't do anything and leave it all to applications