

Sistemi Operativi I

Corso di Laurea in Informatica
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SAPIENZA
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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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Another Synchronization Problem

- 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!)

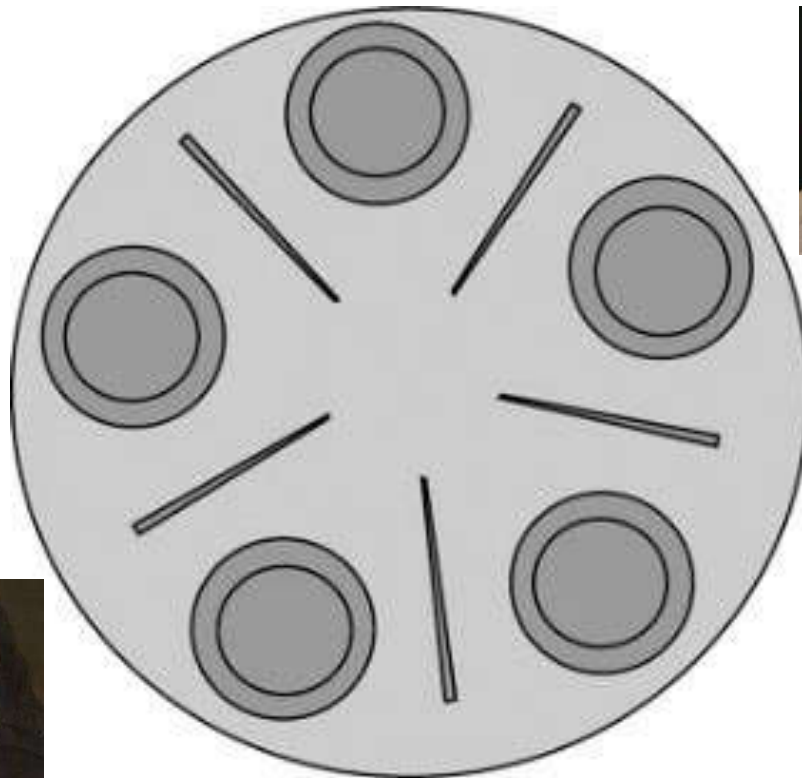
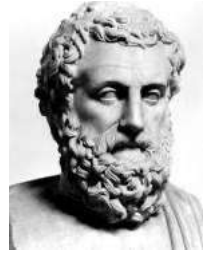
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 - Block if a neighbour has already picked up a chopstick

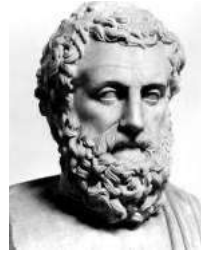
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- After eating, put down both chopsticks and go back thinking!

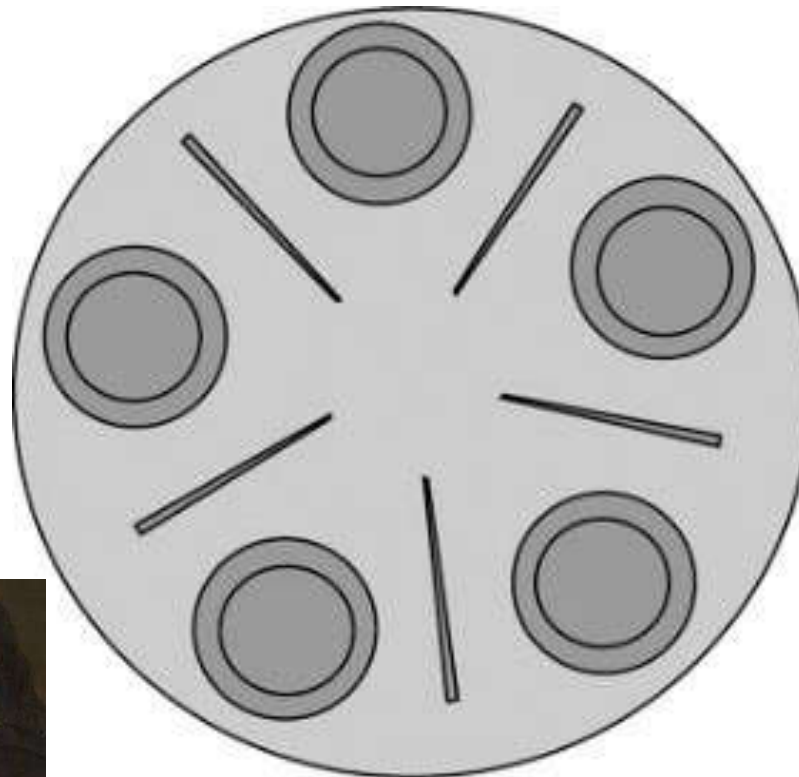
The Dining Philosophers



The Dining Philosophers



How to make them not starving?



The Dining Philosophers

What's the trivial solution to the dining philosophers problem?

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Have a "global" lock which allows a single philosopher to pick both chopsticks

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

    eat();

    chopsticks[i].signal();        // signal on the left chopstick
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    think();
}
```

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Is this solution correct?

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    think();
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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) {
        this.philosophers[i].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

- The problems we have seen so far are interesting because they identify some patterns which are very common in practice
 - 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
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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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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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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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printer.wait();  
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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Intuitively, a condition where two or more threads are waiting for an event that can only be generated by the very same threads

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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B executes again and blocks

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Thread **B**

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printer.wait();
```

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

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

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

Deadlock: Terminology

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- **Deadlock prevention (offline)**: imposes restrictions/rules on how to write deadlock-free programs
- **Deadlock avoidance (online)**: runtime support checks resource requests made by threads to avoid deadlocks

Deadlock vs. Starvation

- Not to be confused with each other!

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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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 - **No Preemption** → a thread can only release a resource voluntarily; neither another thread nor the OS can force it to release the resource
 - **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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Deadlock Detection: Resource Allocation Graph

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

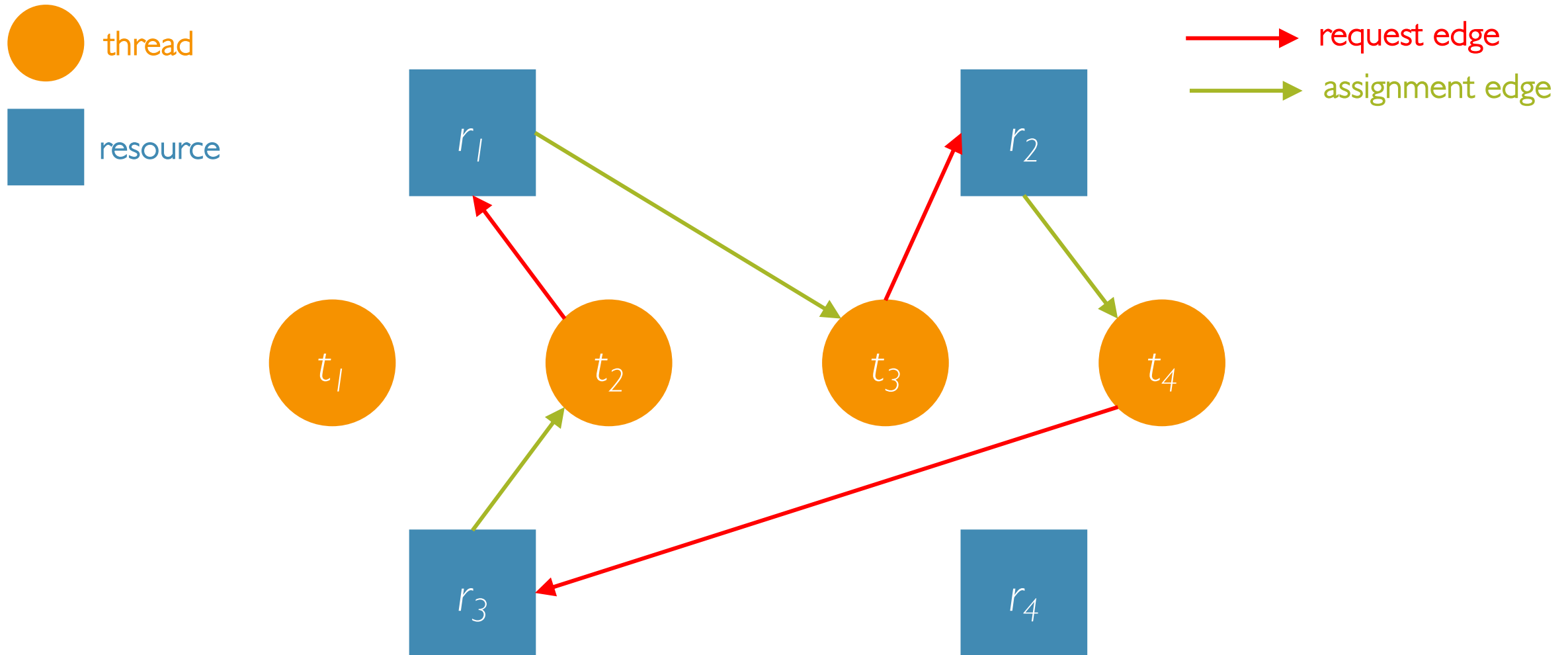
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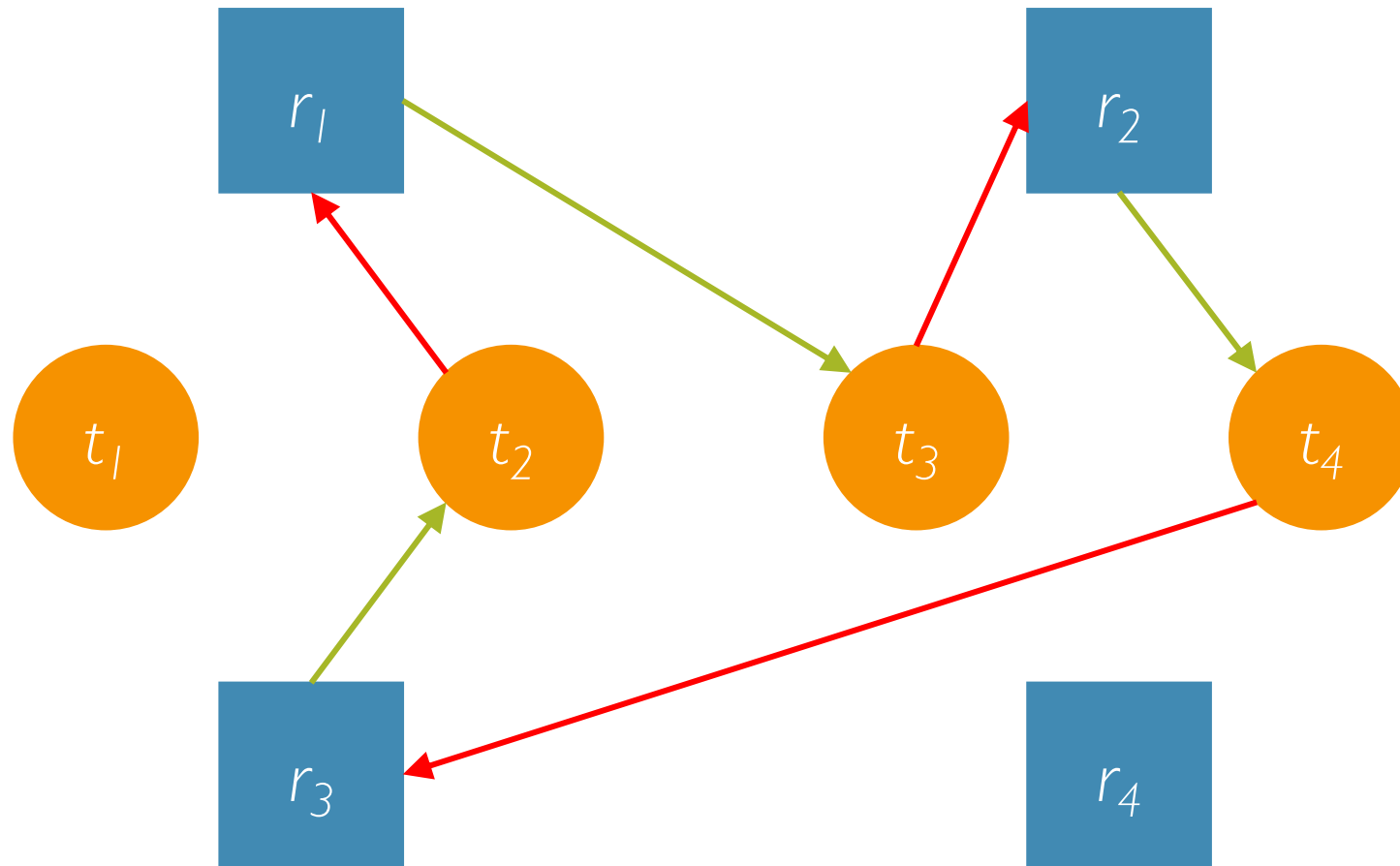
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 - **Assignment Edge** \rightarrow a directed edge (r_j, t_i) indicates that the OS has allocated r_j to t_i

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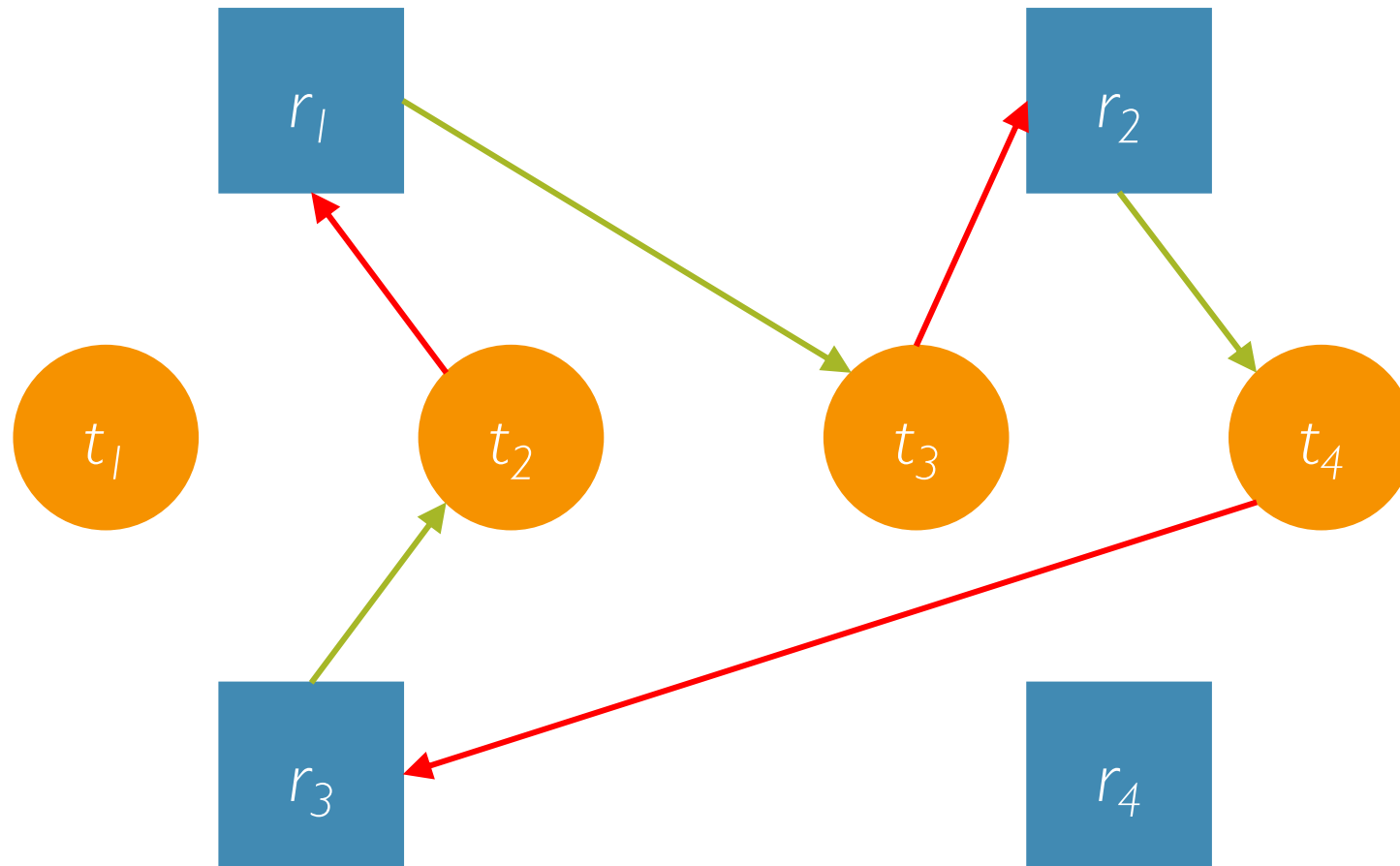


Deadlock Detection: Resource Allocation Graph



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

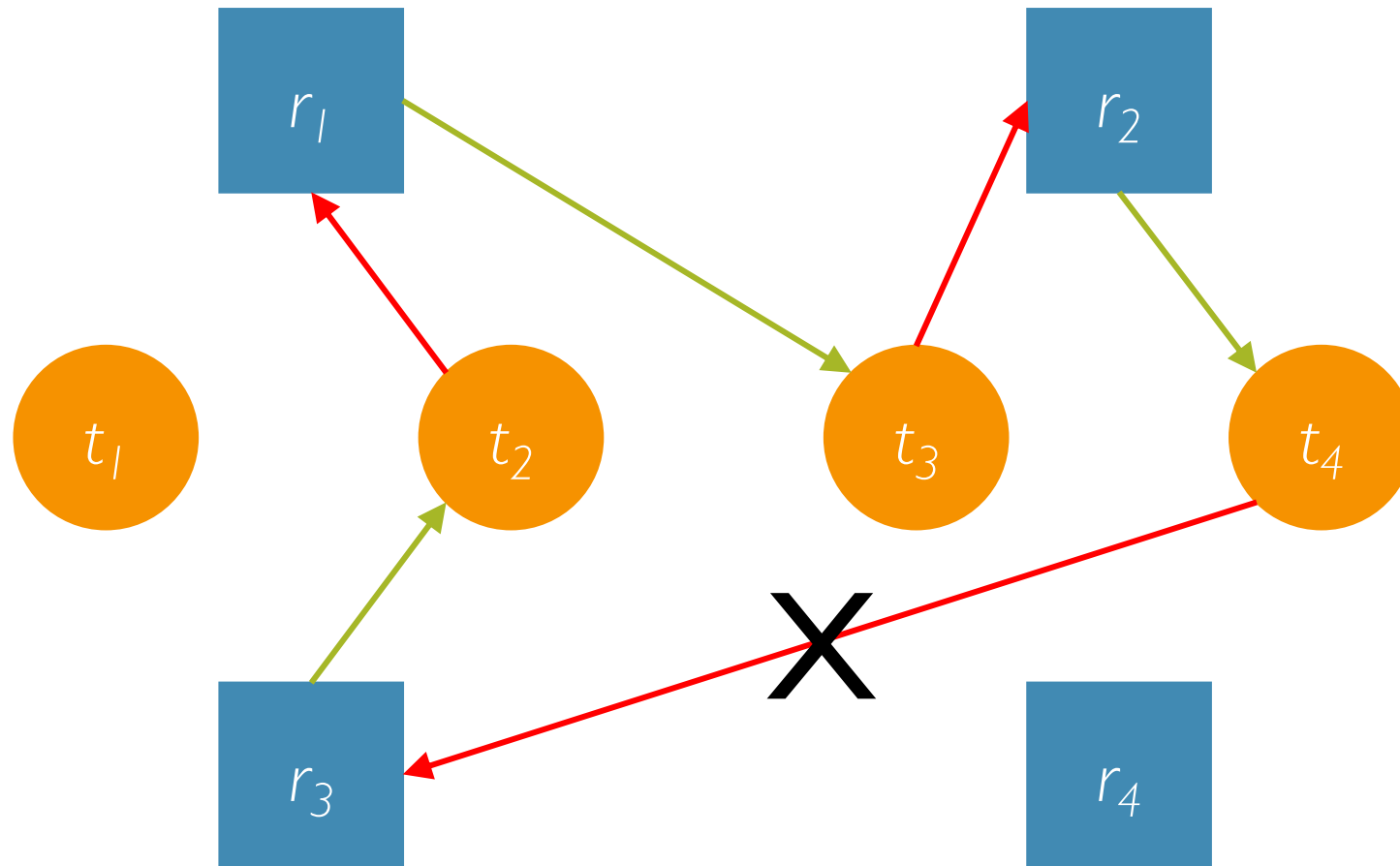
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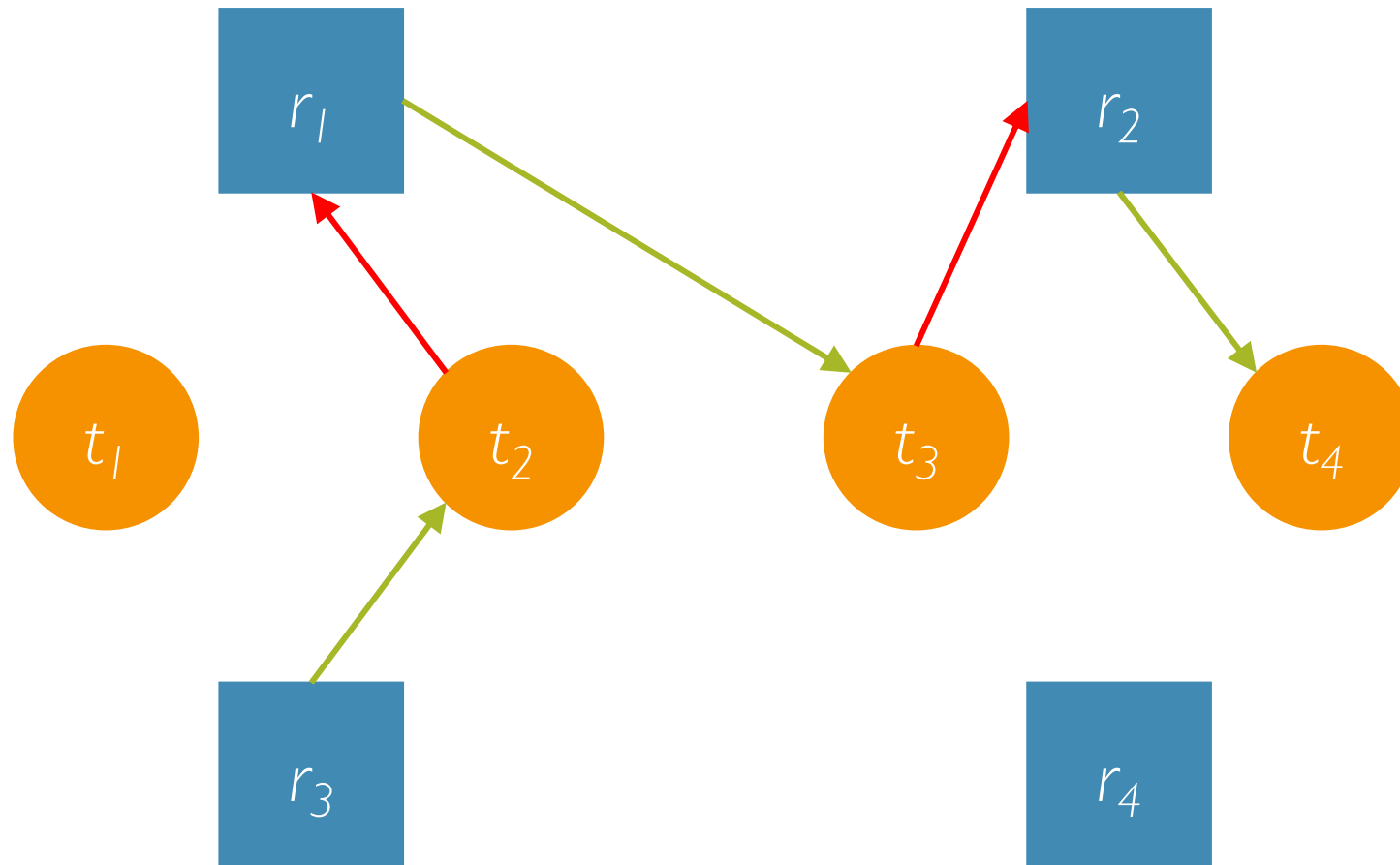
Why?

Deadlock Detection: Resource Allocation Graph



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

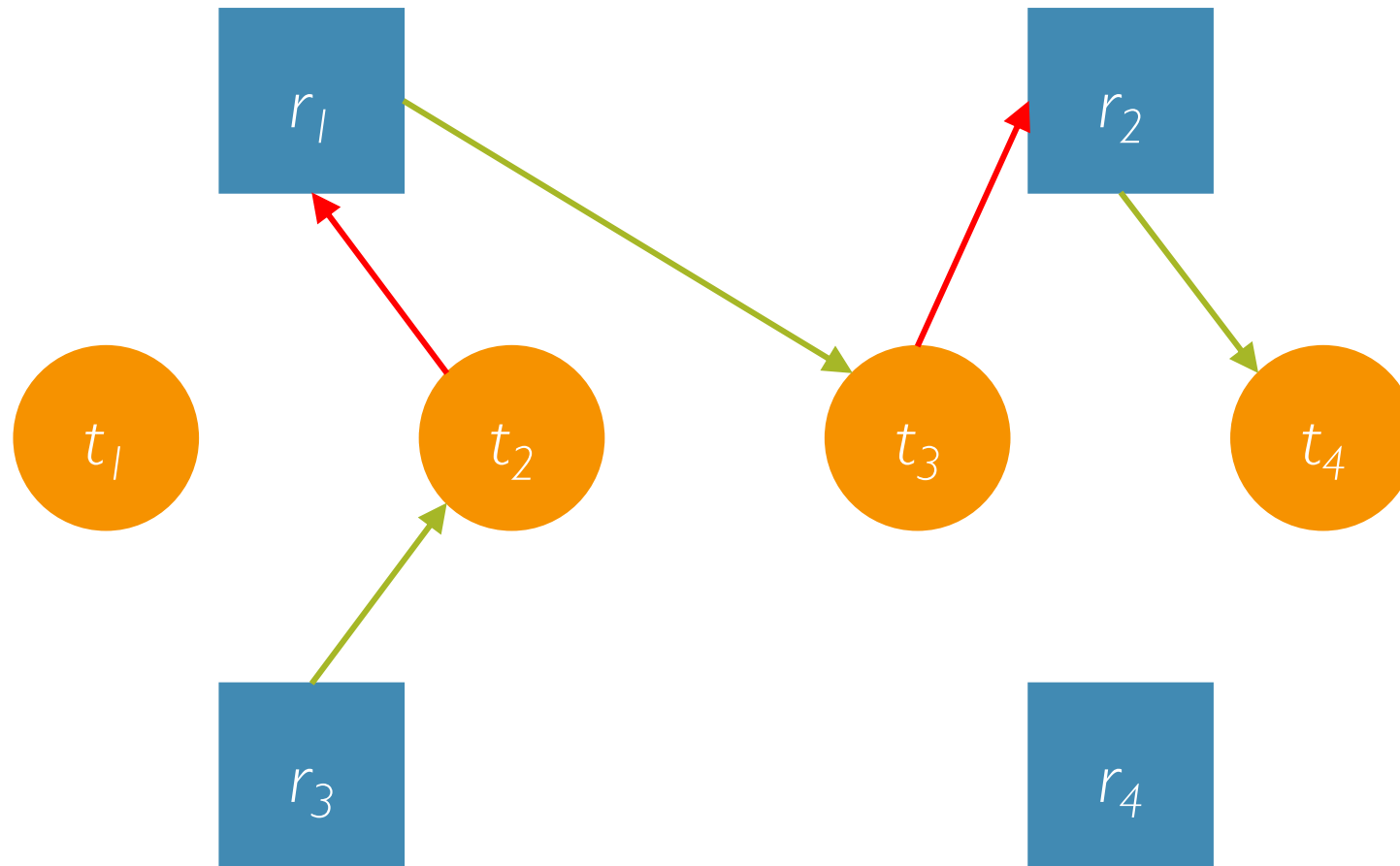
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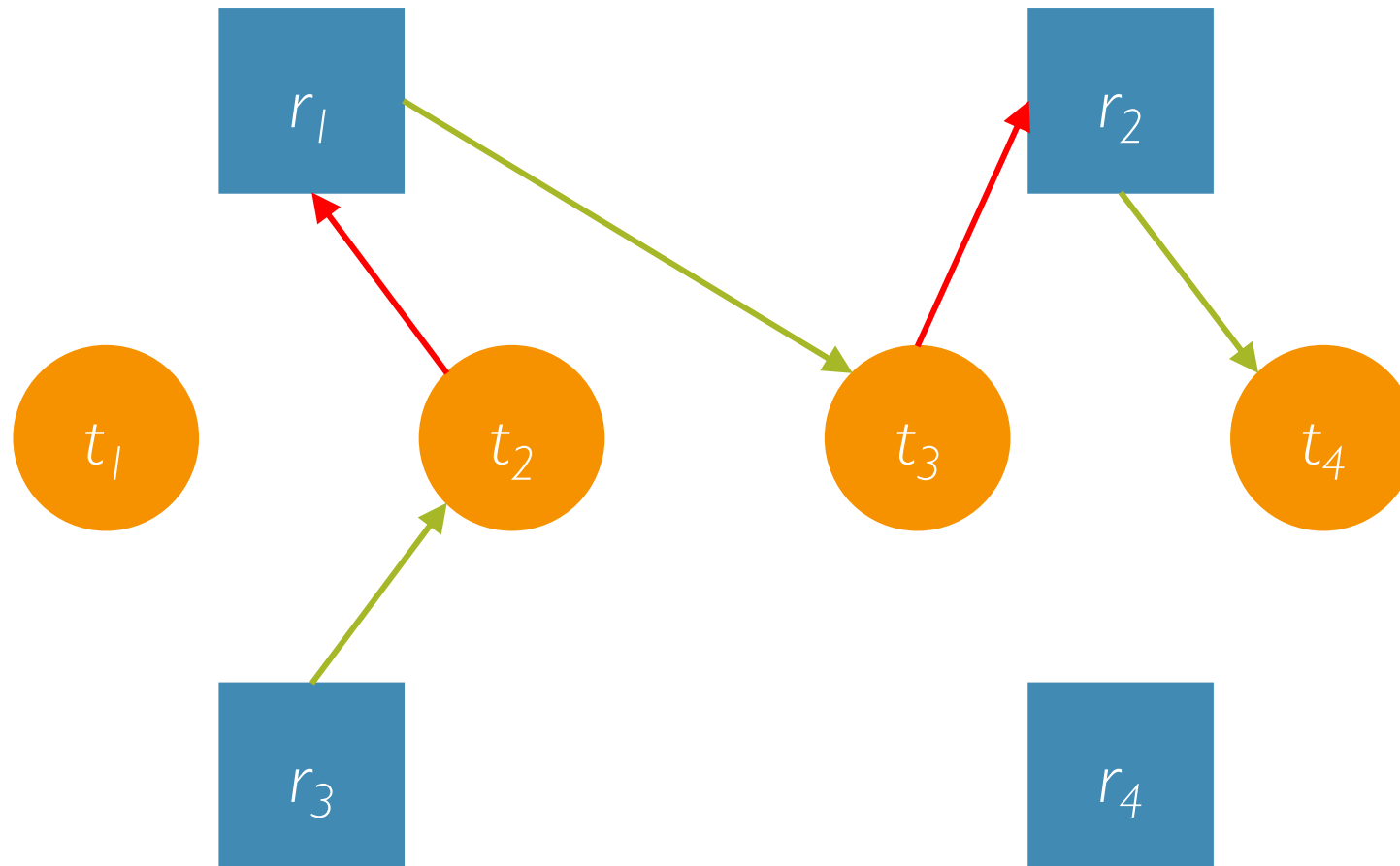


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Therefore, t_4 can run and eventually will release r_2 , which wakes up t_3

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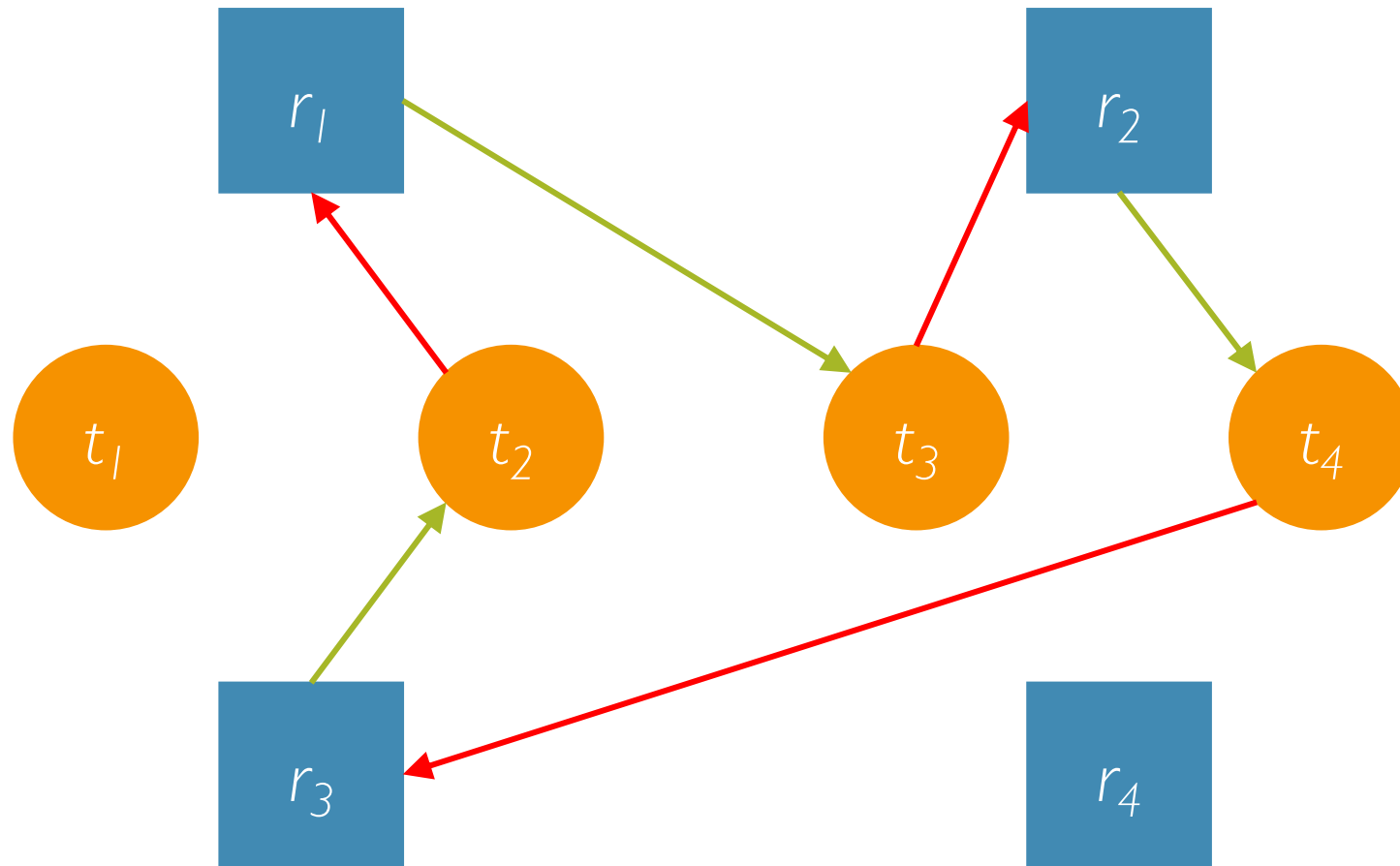
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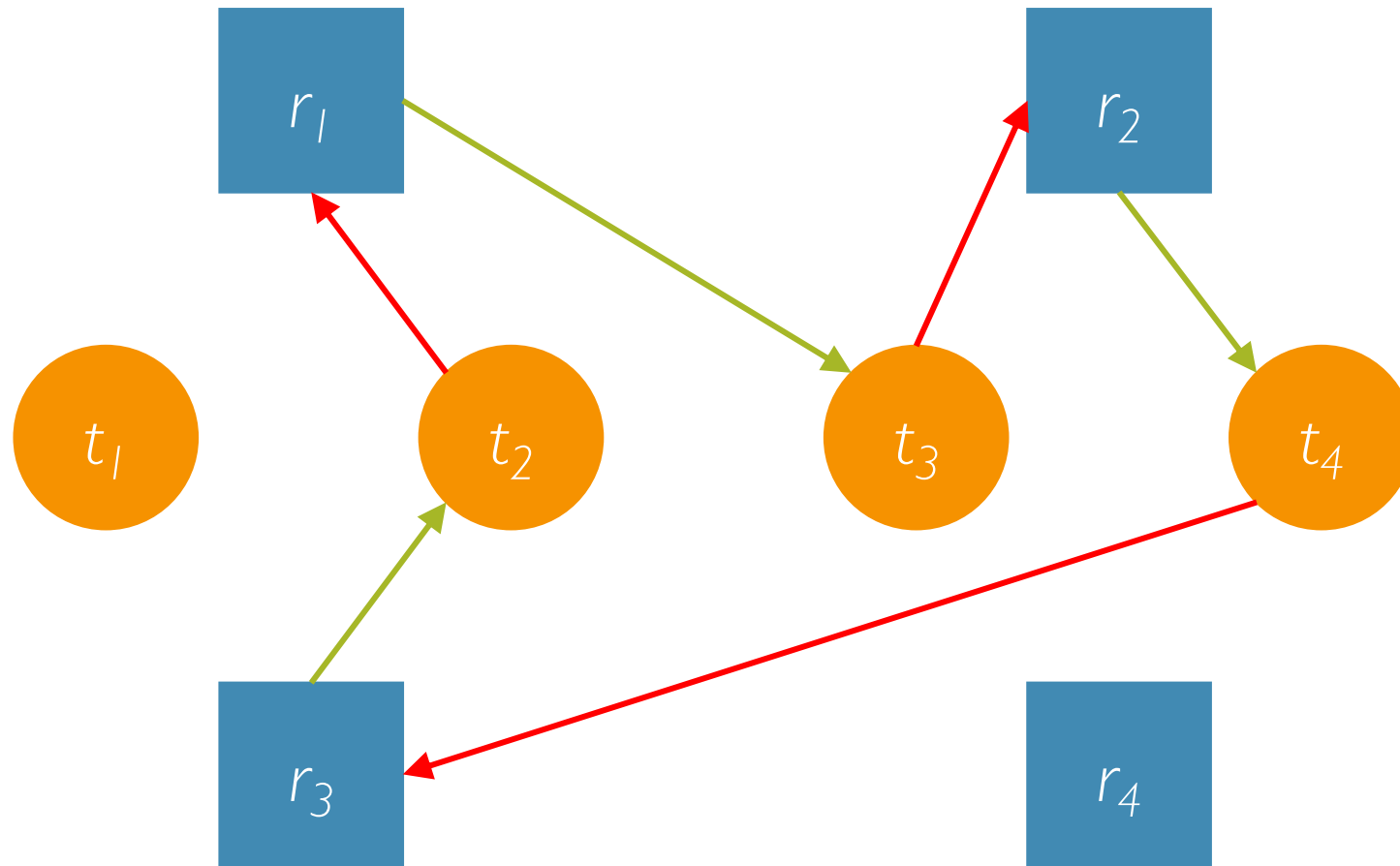
And so on and so forth...

Deadlock Detection: Resource Allocation Graph



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

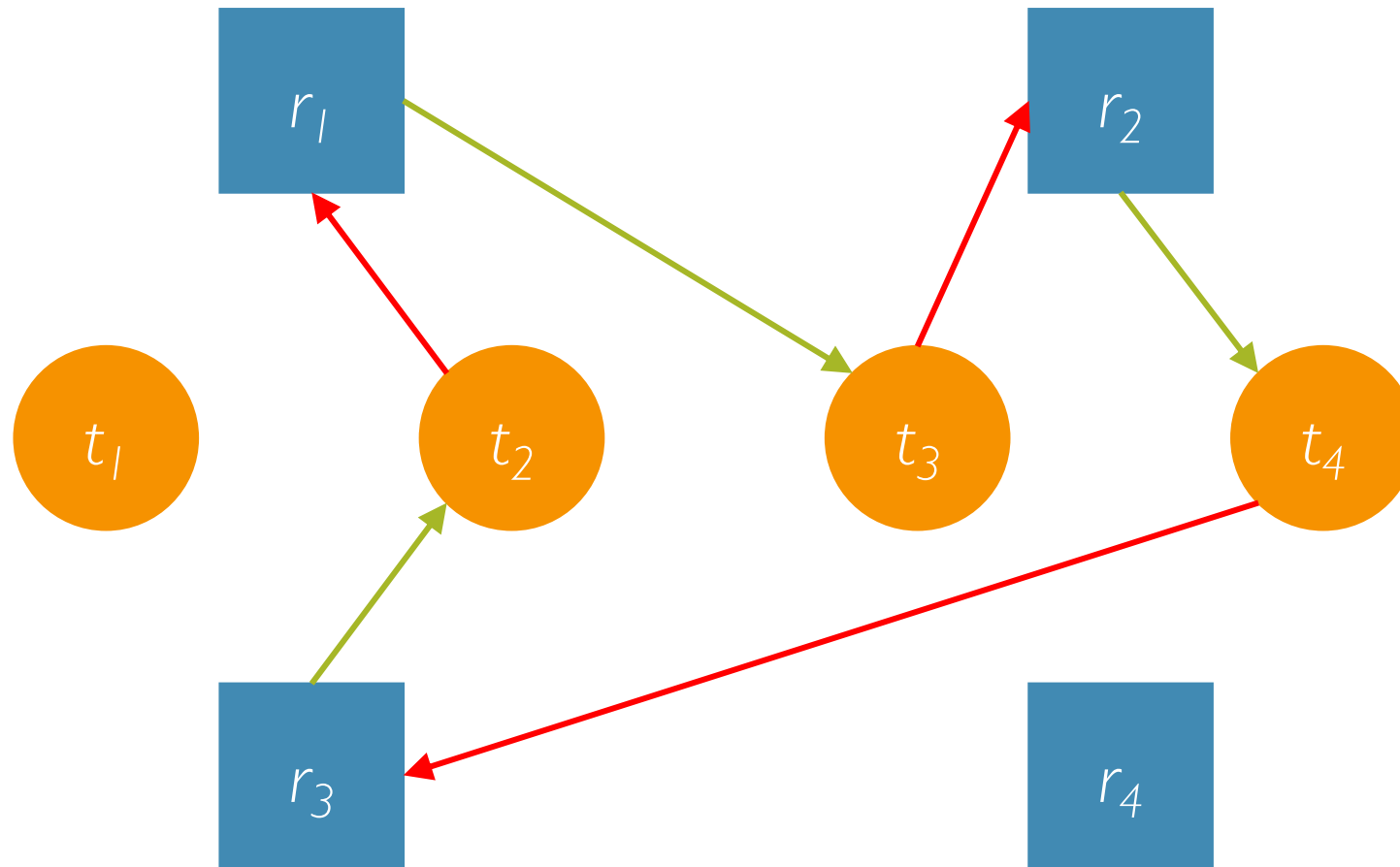
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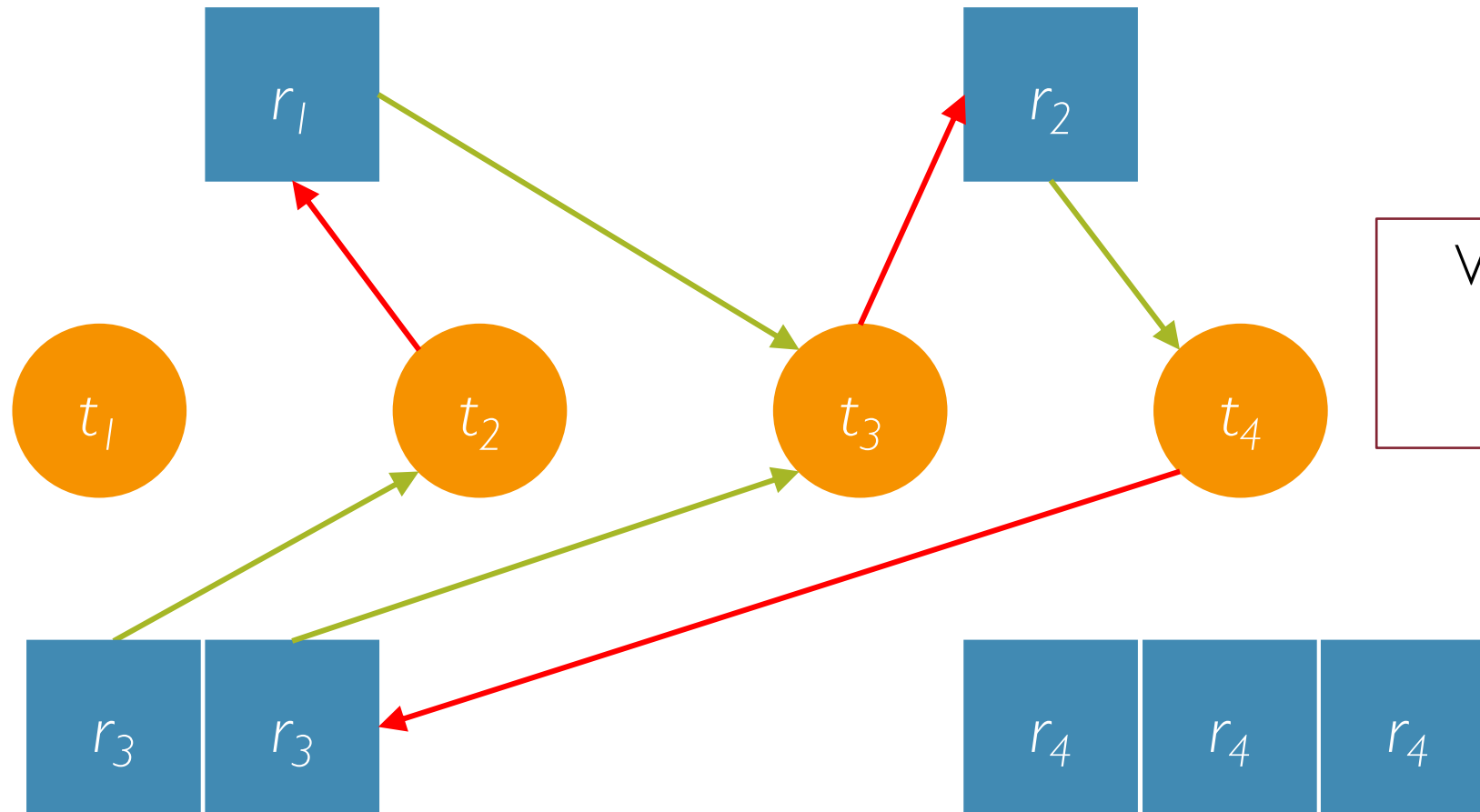
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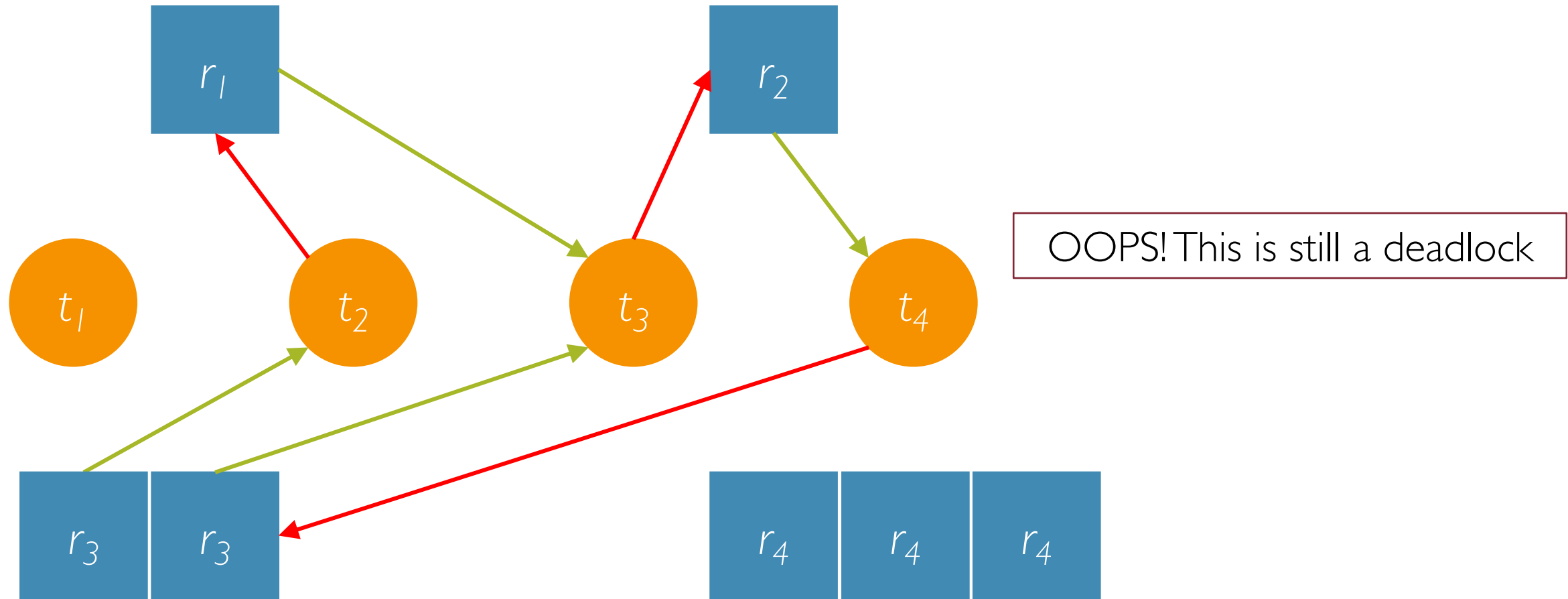
We are implicitly assuming the **multiplicity** of each resource is 1 (i.e., we have one r_1 , one r_2 , etc.)

Deadlock Detection: Resource Allocation Graph

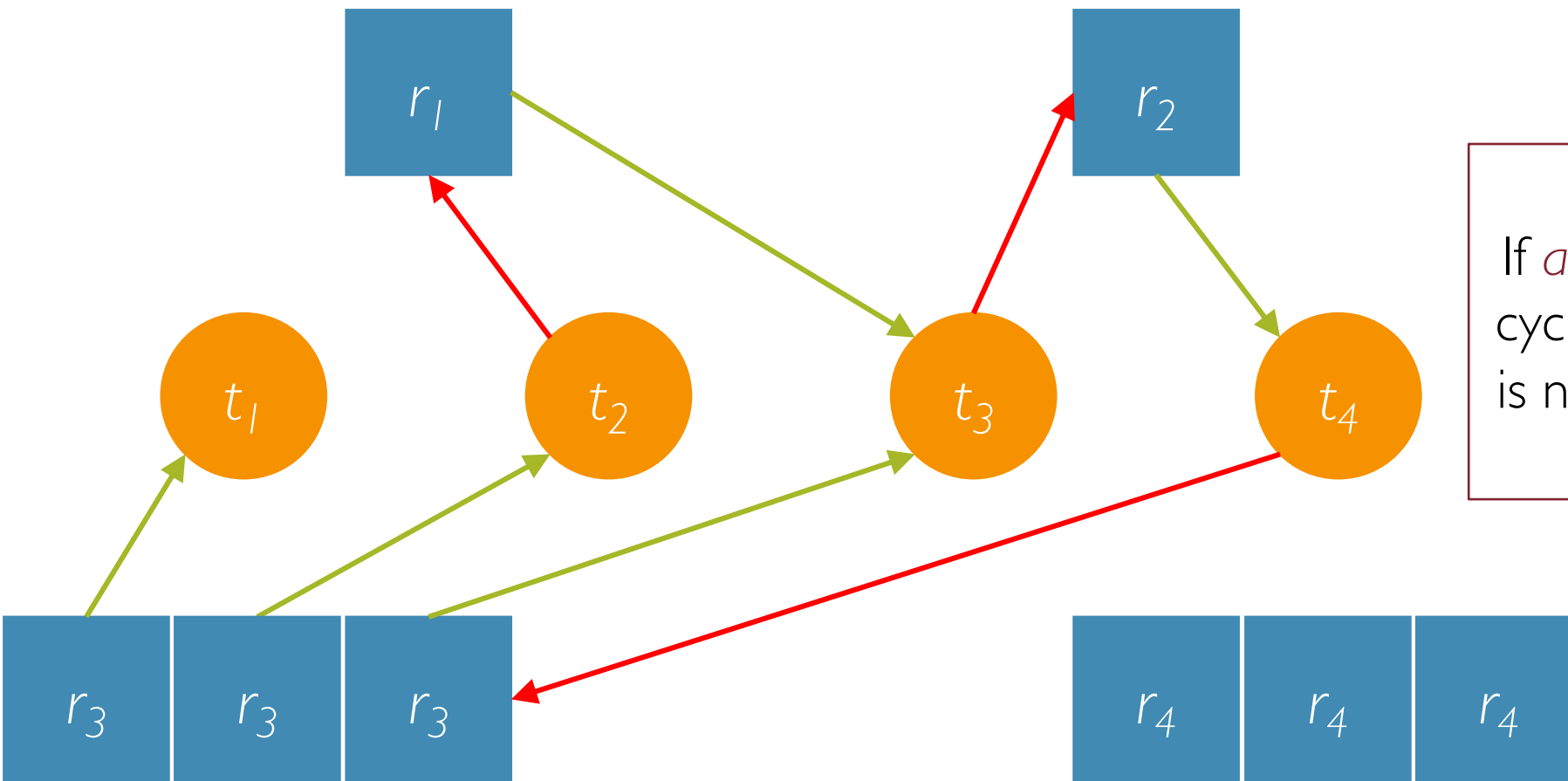


What if there are **multiple** instances of the same resource?

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?)
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 - 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

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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	$m_i - c_i$
t_1	4	3	1
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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

- 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

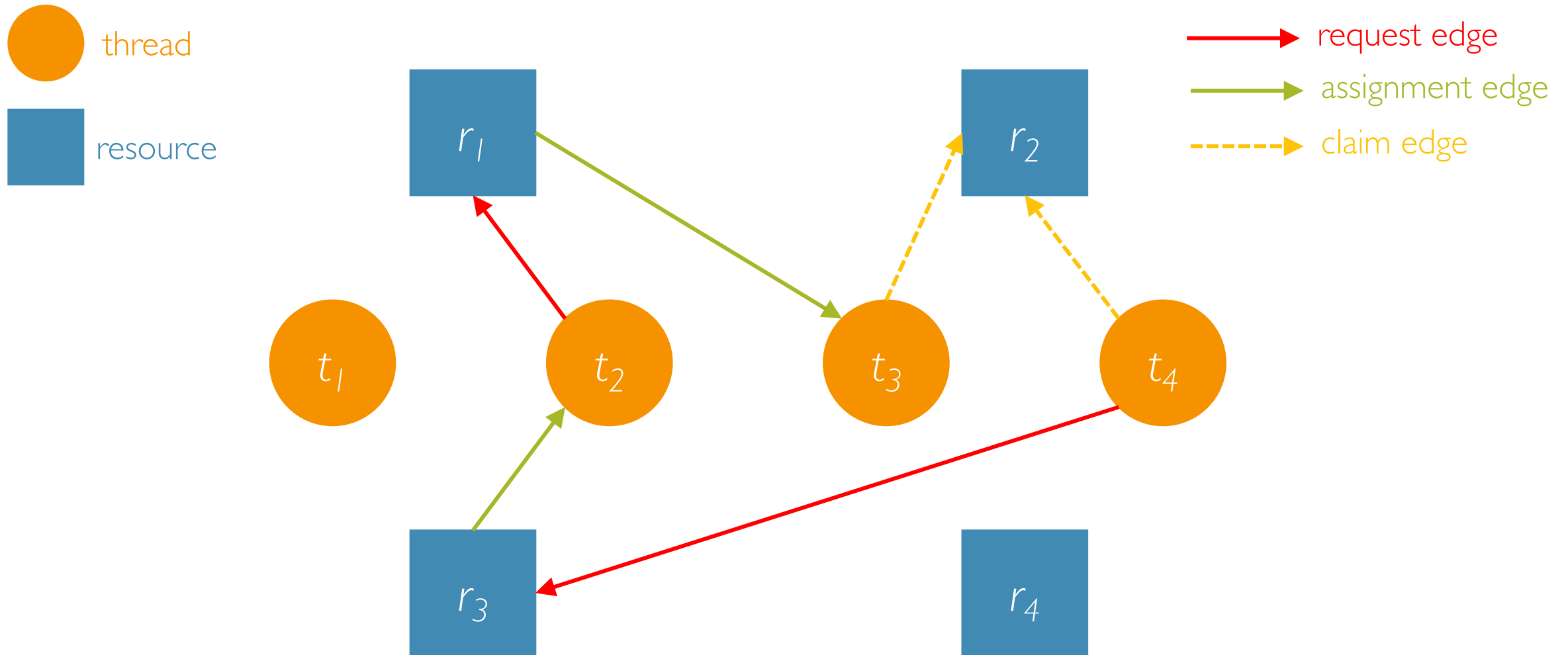
Deadlock Avoidance: Resource Allocation Graph

- 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

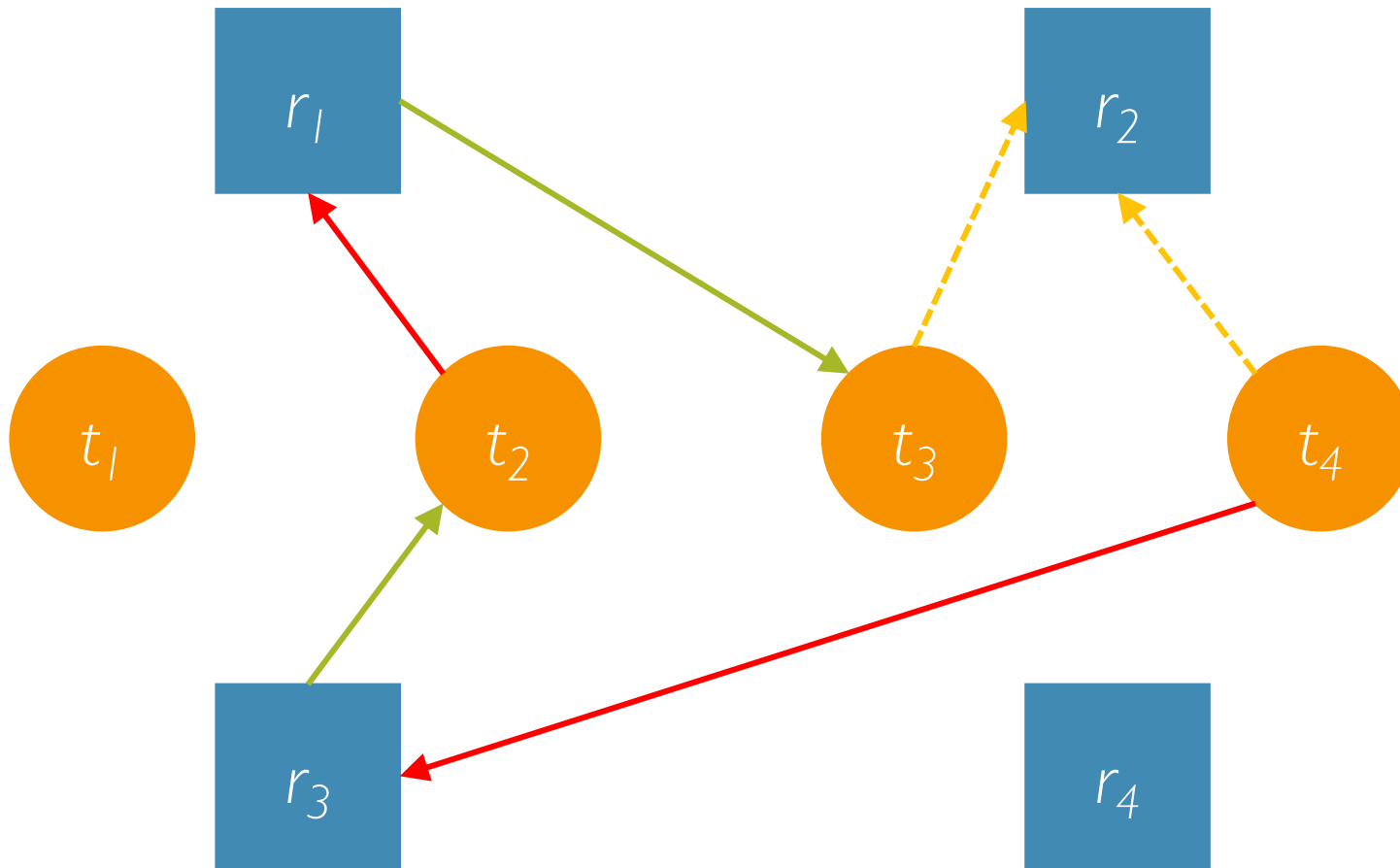
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- A cycle in this extended RAG indicates an unsafe state
- If the allocation results in an unsafe state, this will be denied even if the resource is actually available
- In other words, the claim edge is converted into a request edge and the thread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

Deadlock Avoidance: Resource Allocation Graph

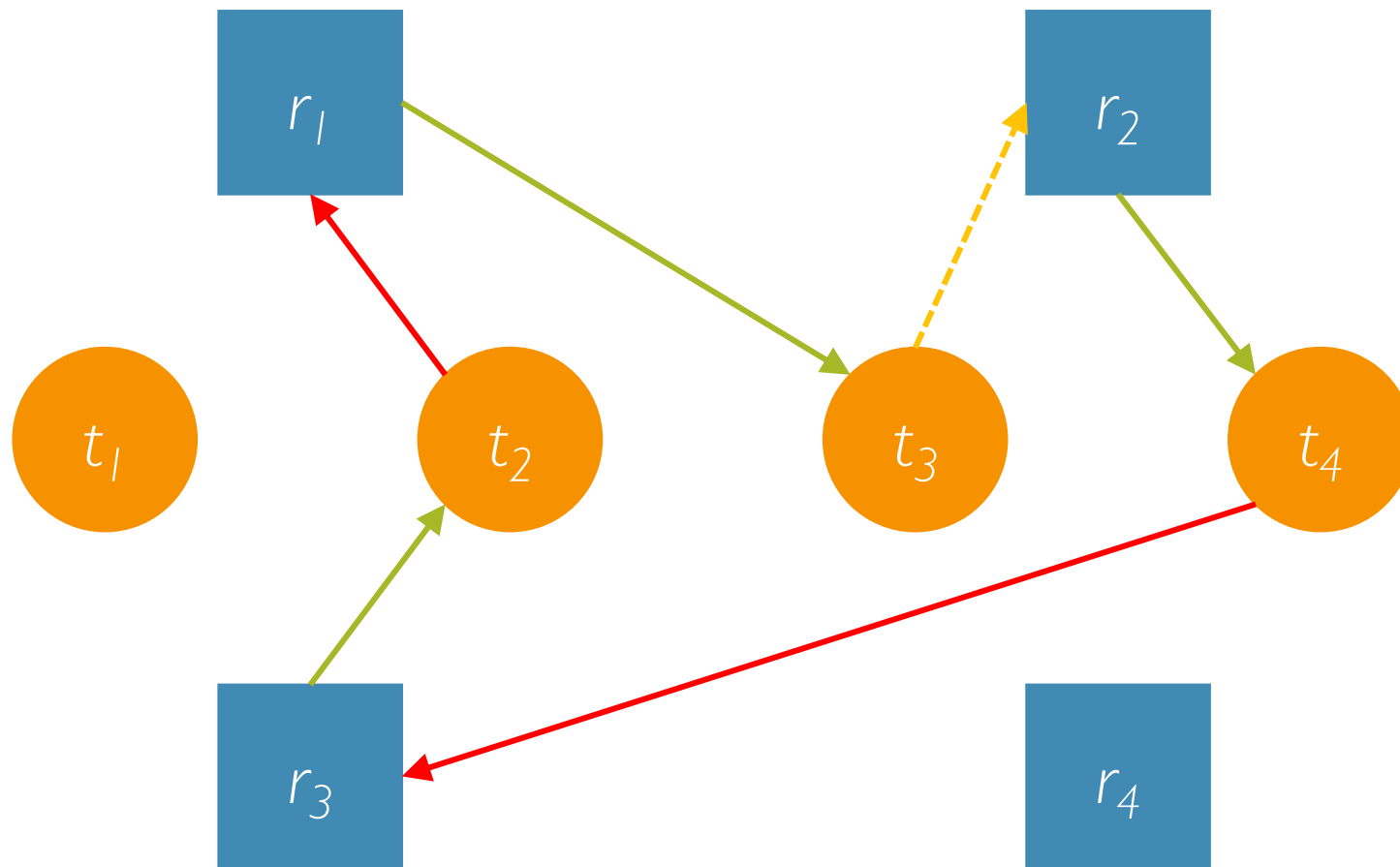


Deadlock Avoidance: Resource Allocation Graph



What happens if t_4 is given r_2 ?

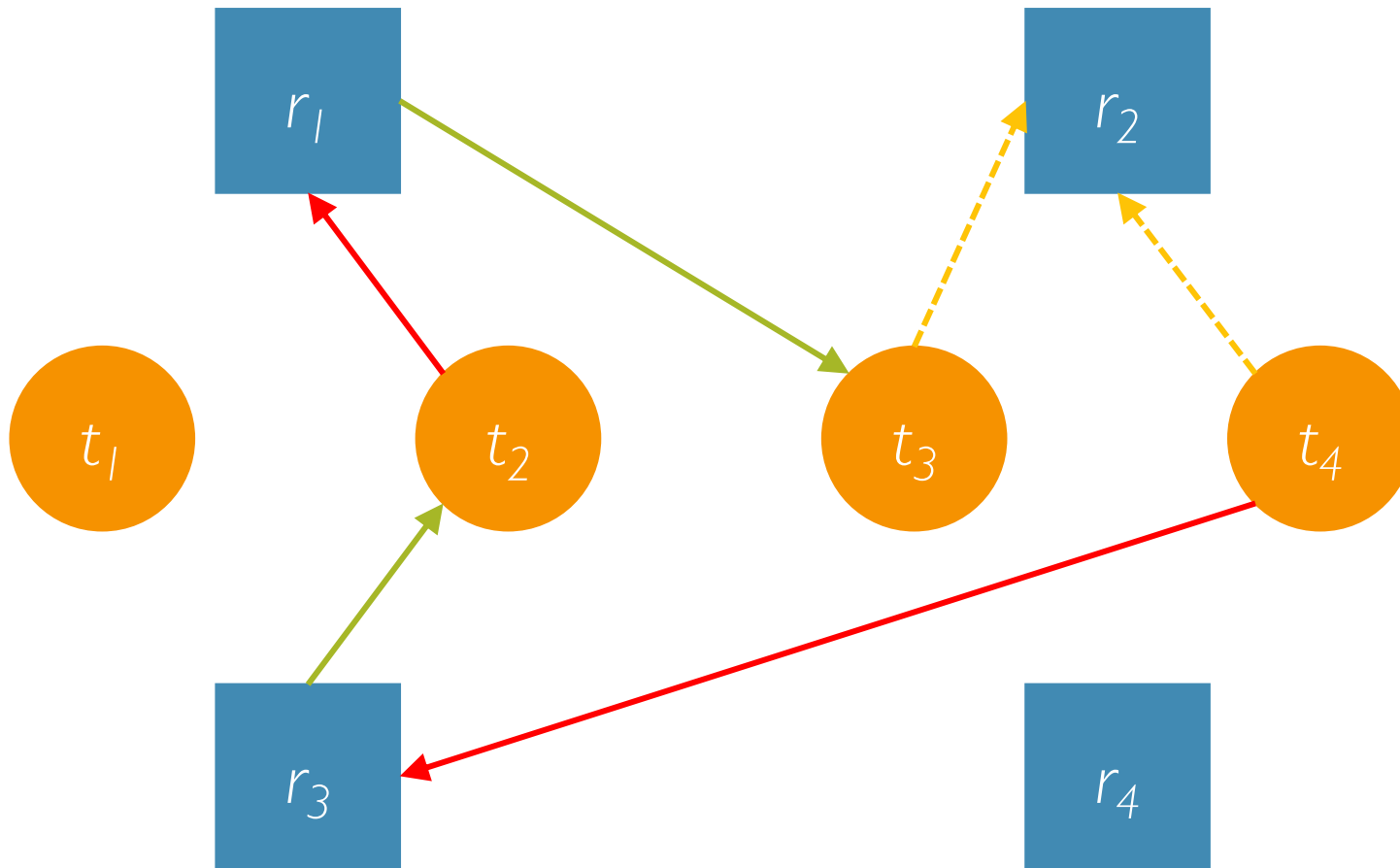
Deadlock Avoidance: Resource Allocation Graph



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

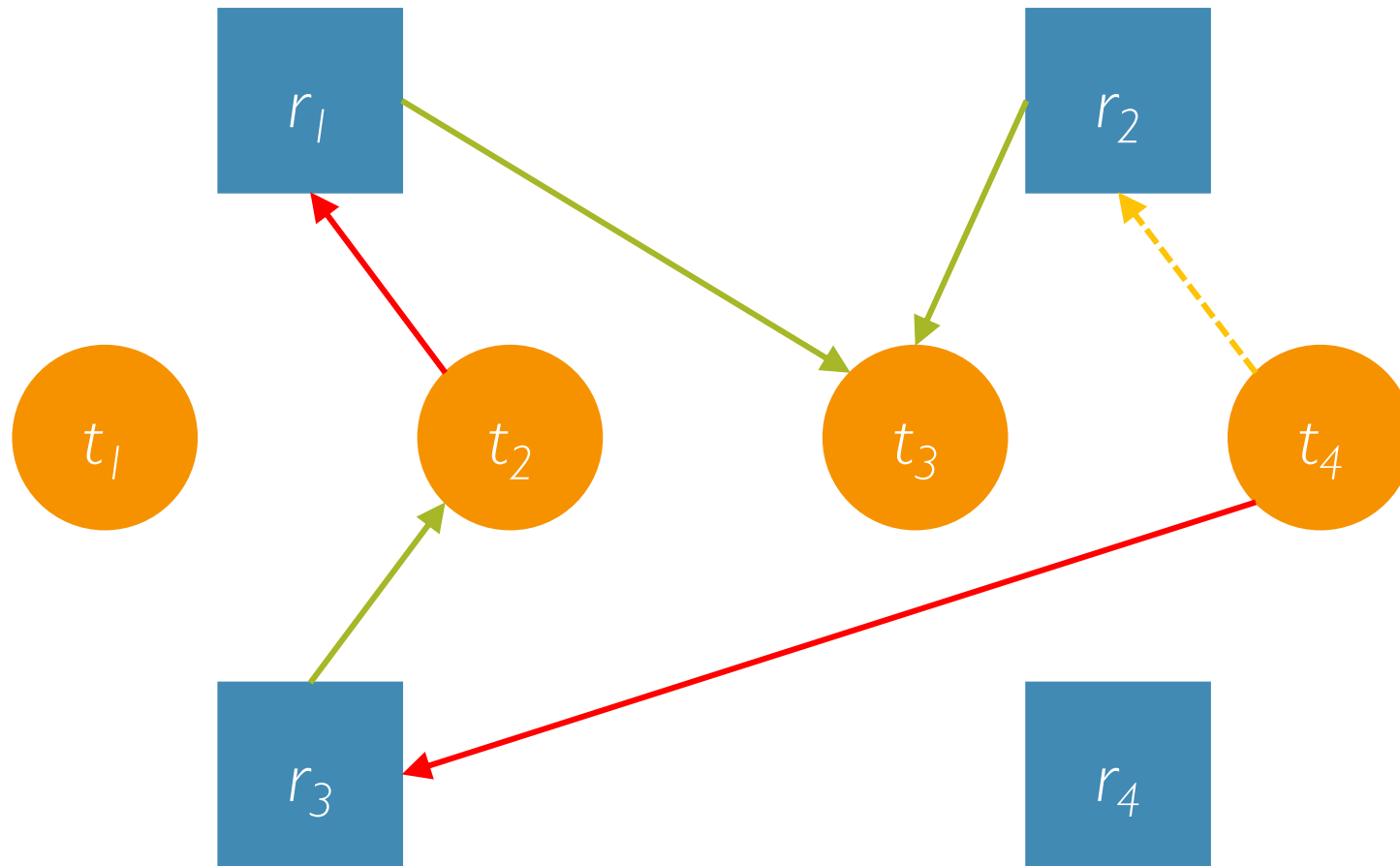
unsafe state

Deadlock Avoidance: Resource Allocation Graph



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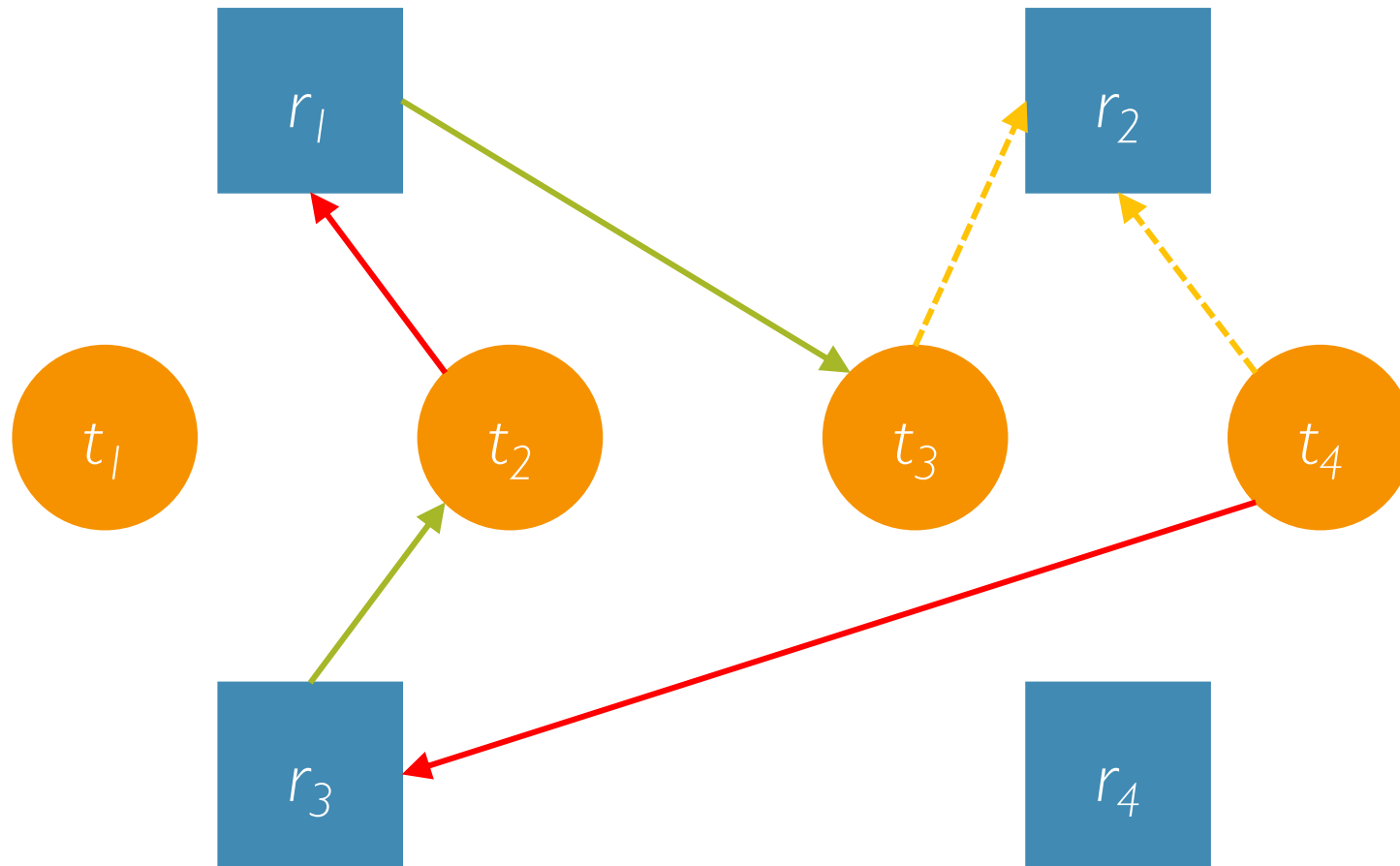
Deadlock Avoidance: Resource Allocation Graph



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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- 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			
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	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

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

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

		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						
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		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						
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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 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						
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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				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									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											
		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	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									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, 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									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

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			
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			
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?

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