Systems and Networking I

Applied Computer Science and Artificial Intelligence

2023-2024

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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

Another Synchronization Problem

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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

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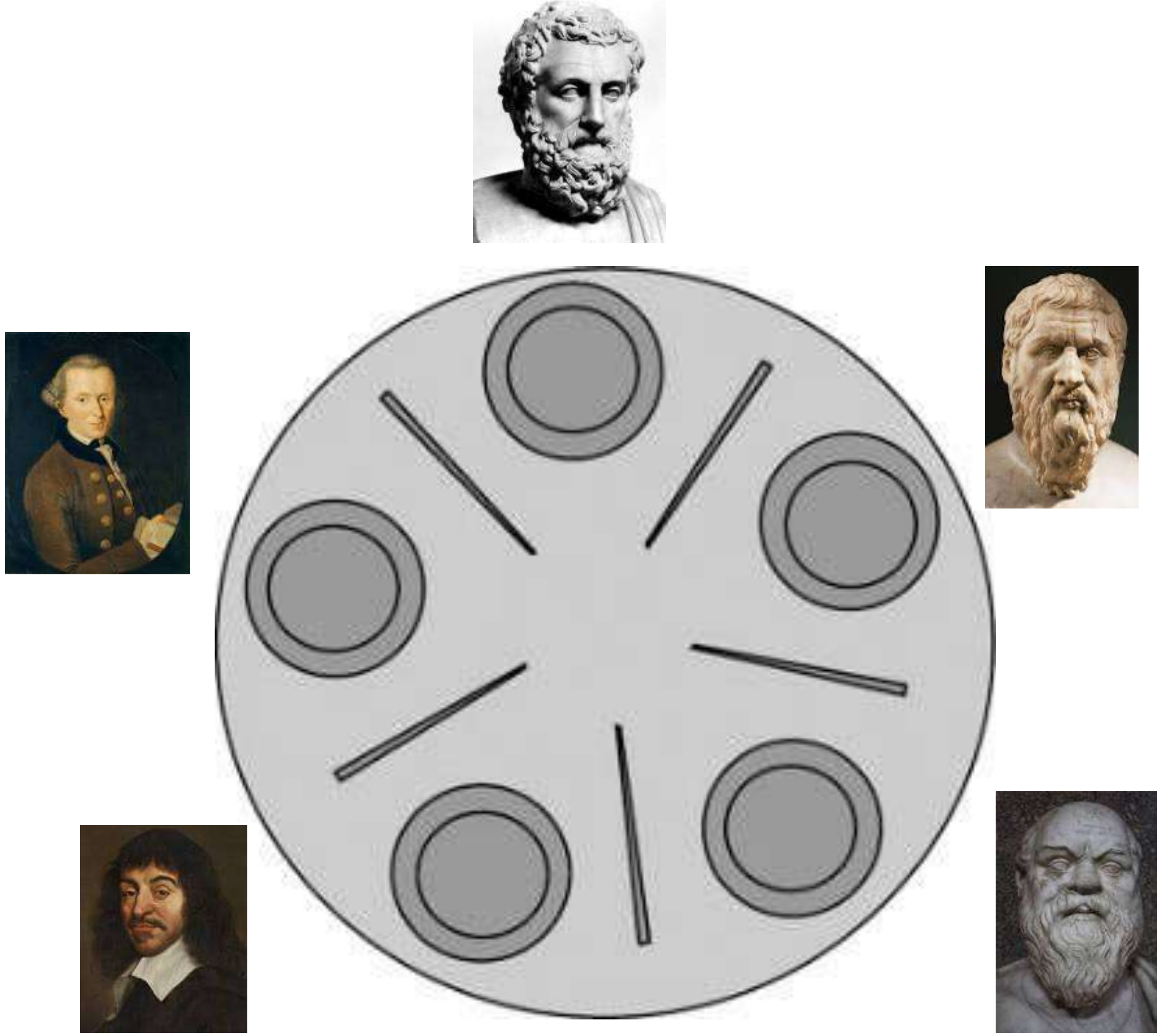
  - Block if a neighbor has already picked up a chopstick
- After eating, put down both chopsticks and go back thinking!

The Dining Philosophers



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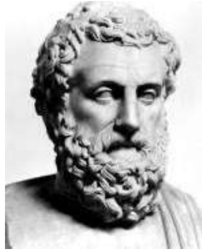
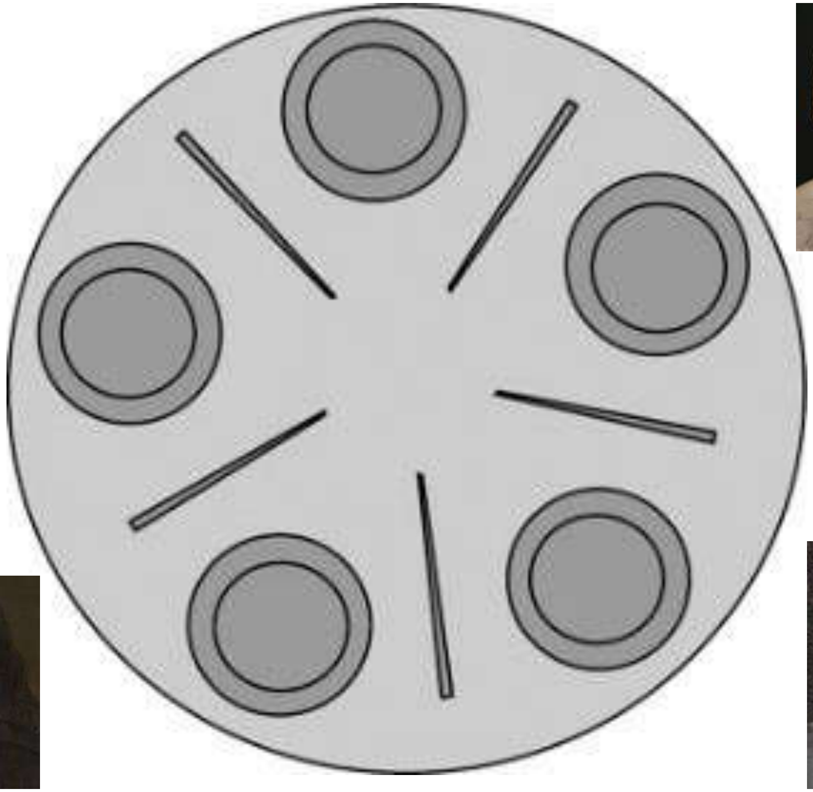
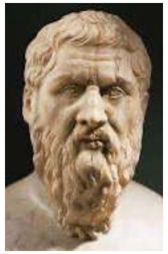
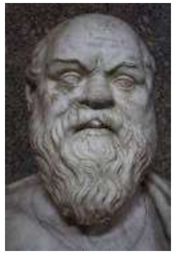


How to make them not starving?







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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 1

```
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?

No! Deadlock if all philosophers take the left chopstick

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

Never gonna pick a single chopstick!

The Dining Philosophers: Solution 2 (monitors)

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

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

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

    public DiningPhilosopers() {
        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);
    while(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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  - Producer-Consumer
    - Audio/Video player embedded in a web browser: shared data buffer + network and render threads
  - Reader-Writer
    - DB system of a bank: 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?
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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

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

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A starts first

Thread B

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printer.wait();

// copy from disk to printer

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

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Acquires printer and context switch

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B takes over

Thread B

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printer.wait();

// copy from disk to printer

printer.signal();
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A executes again and blocks

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B executes again and blocks

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A waits B to release the disk

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Thread B

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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

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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  - 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 $t_1, \ldots, t_n$ where t_i is waiting on $t_{(i+1)\%n}$

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

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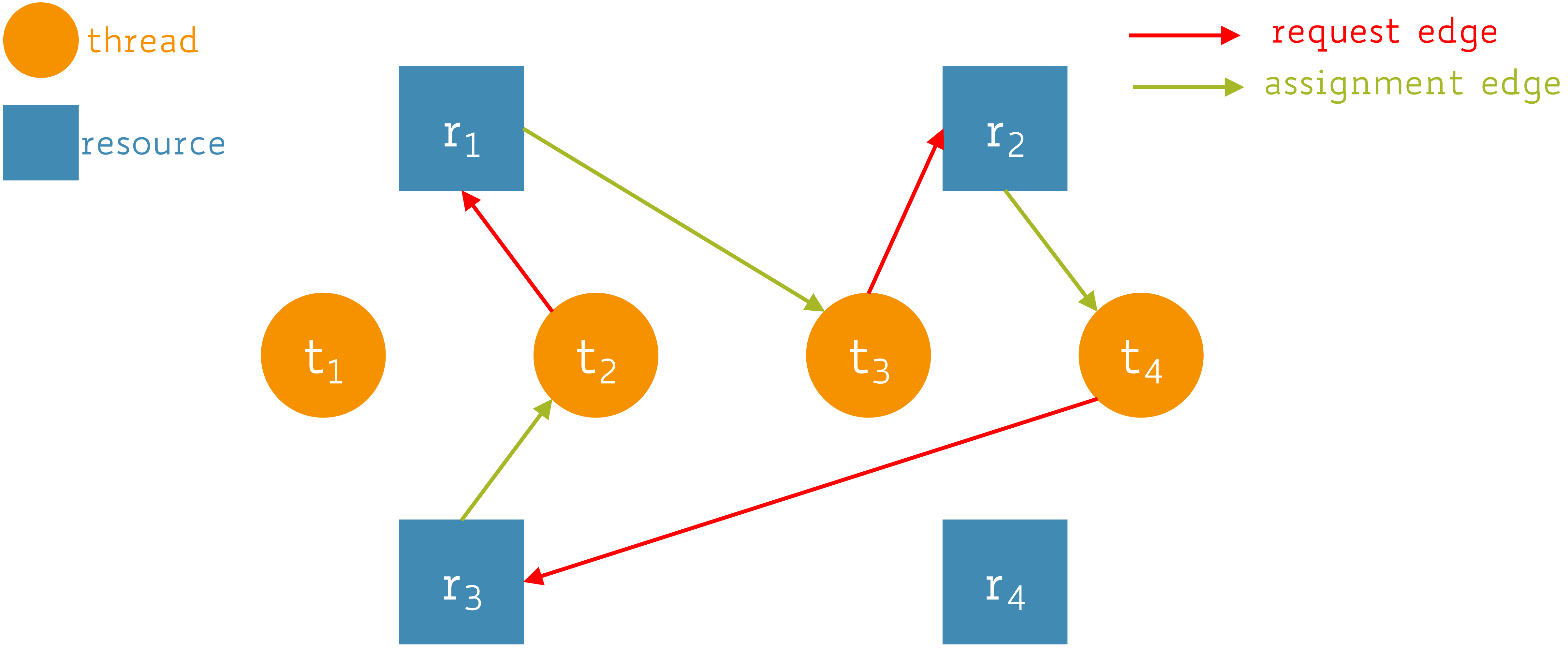

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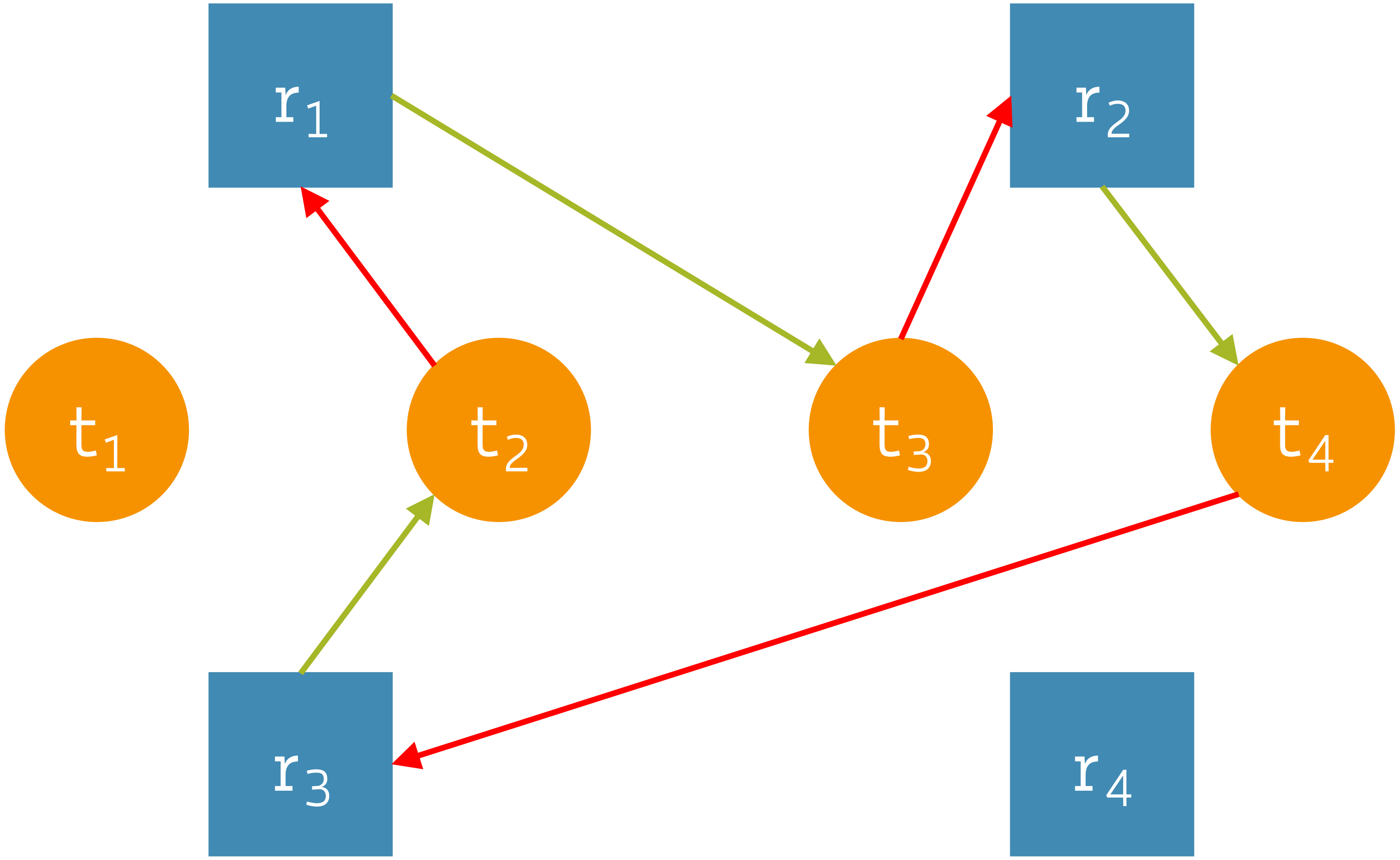

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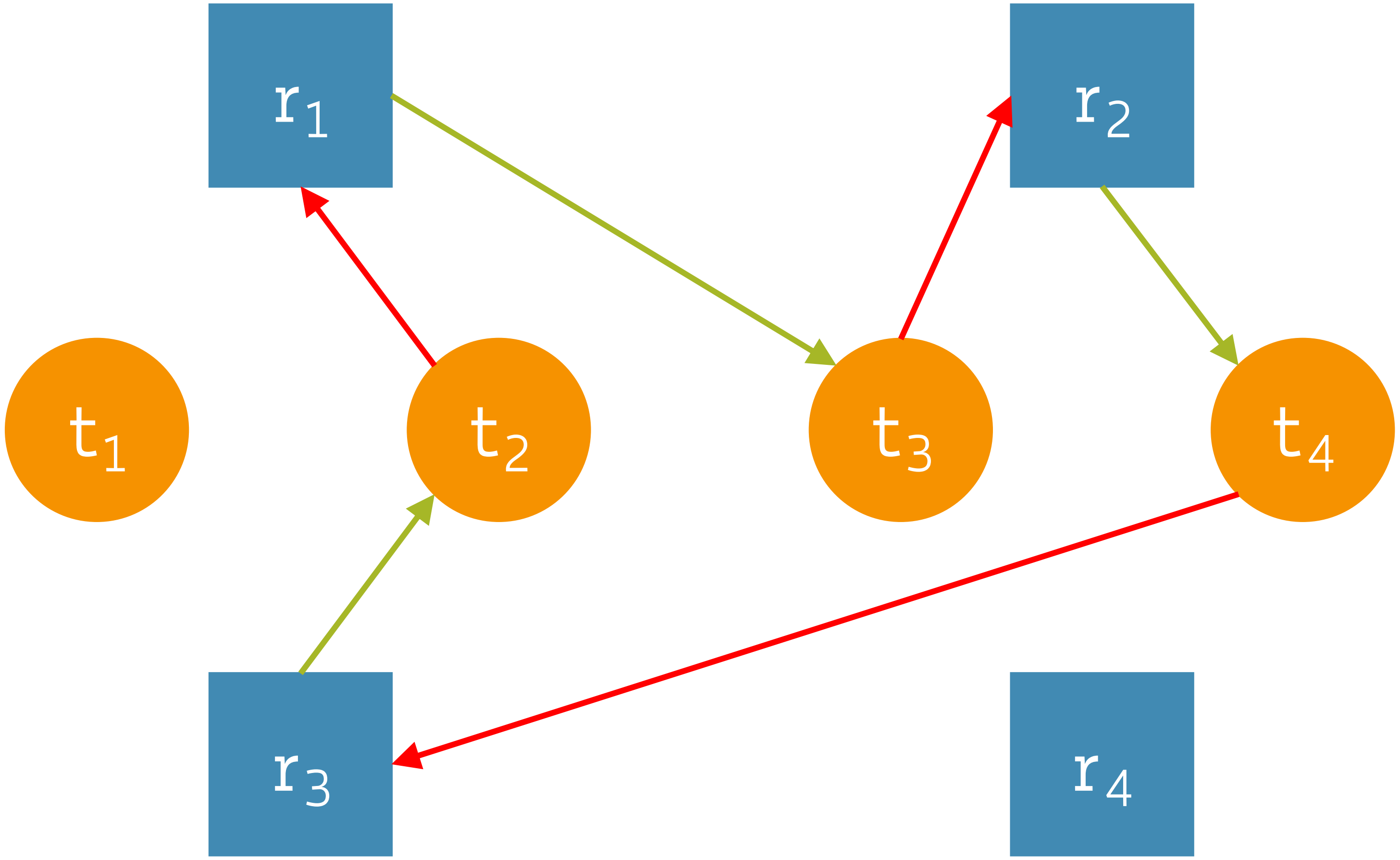

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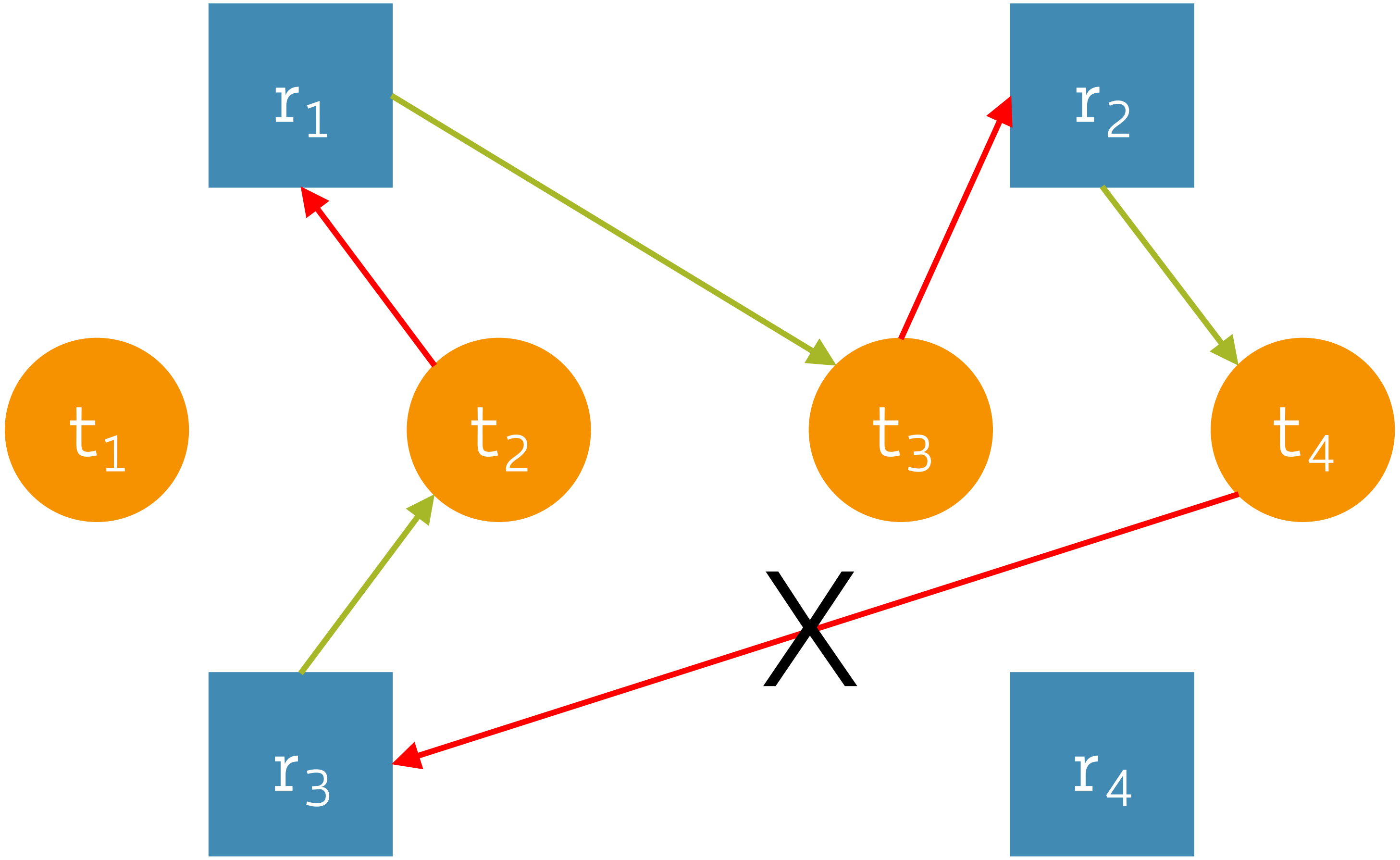

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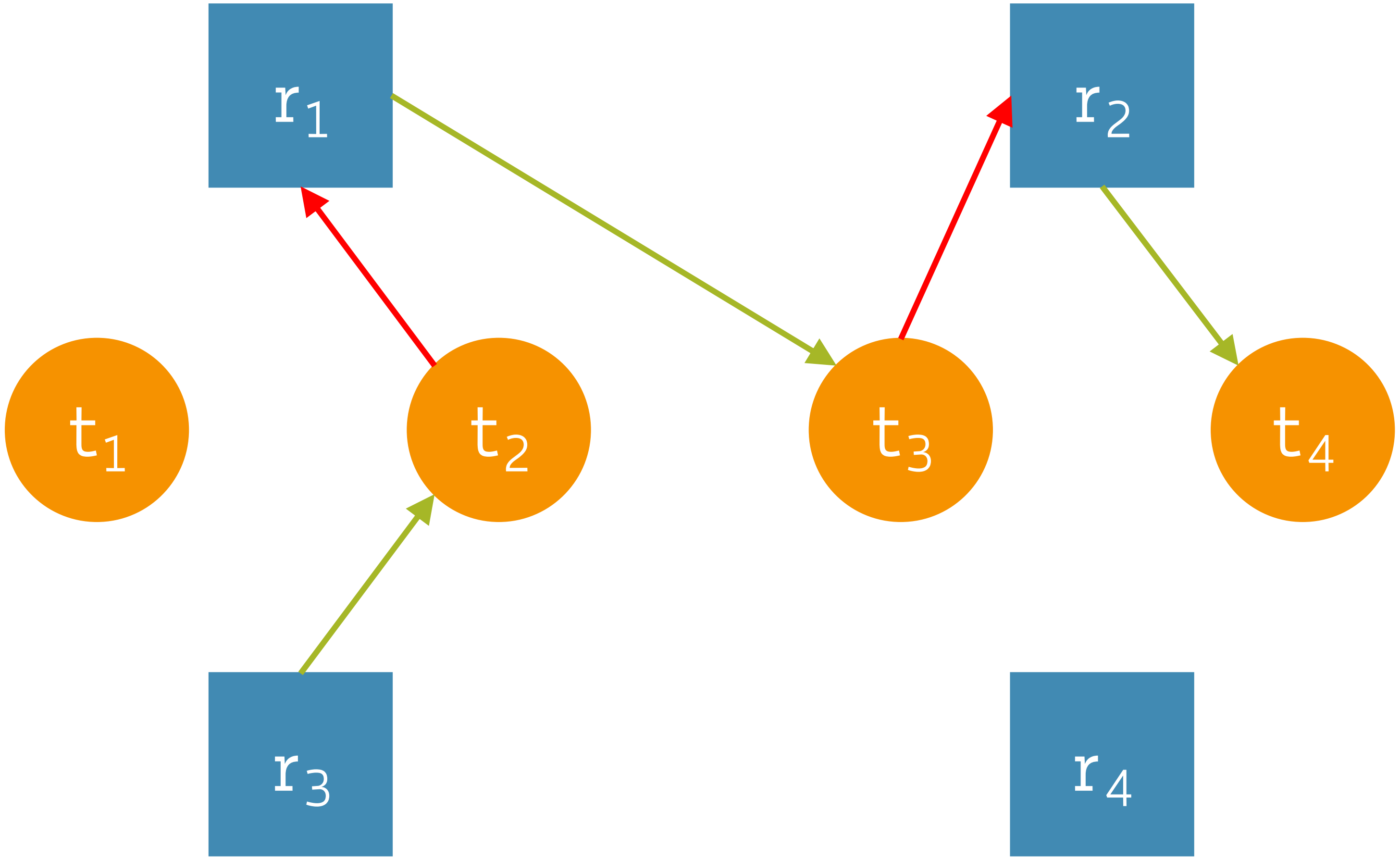

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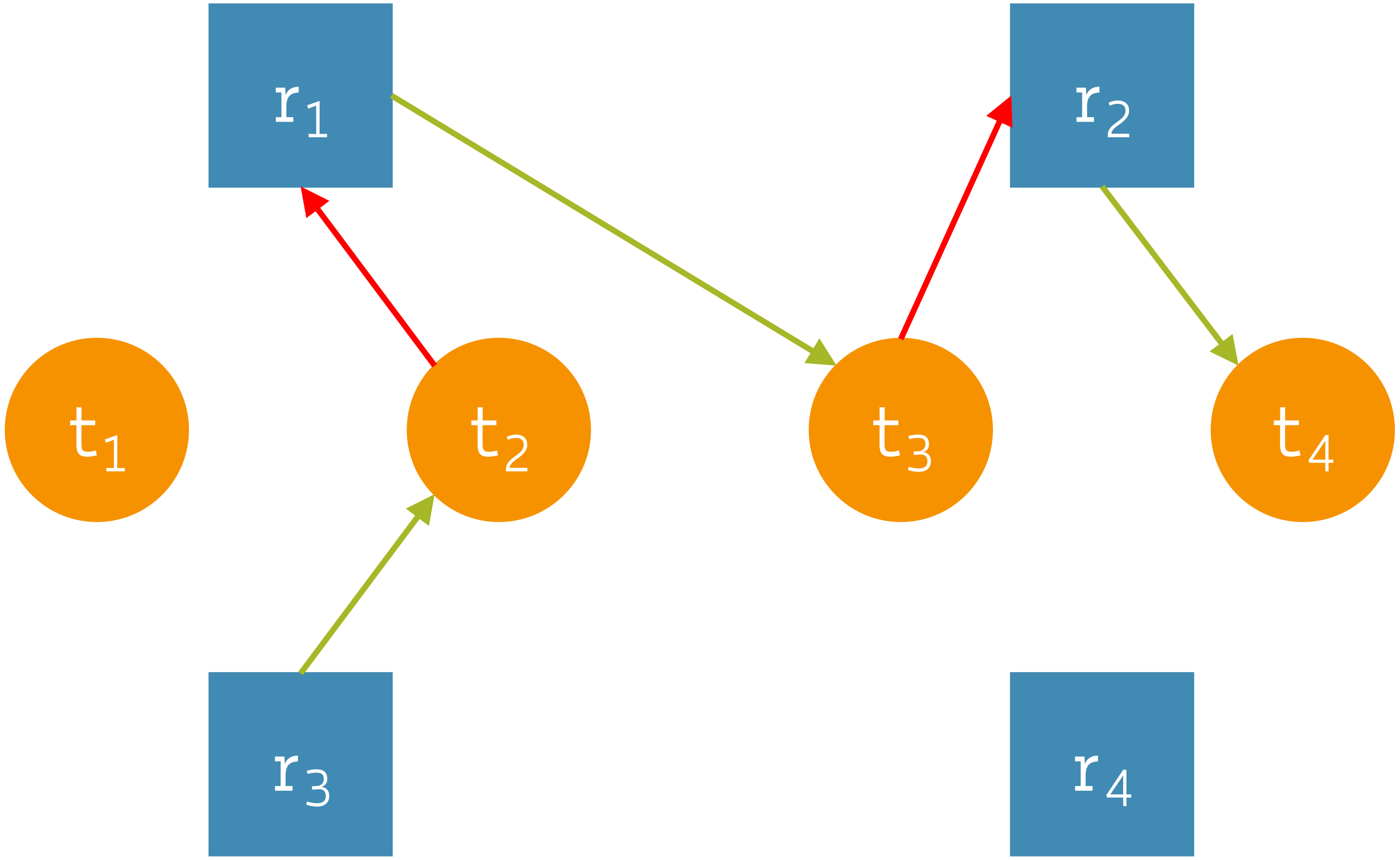

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Therefore, t_4 can run and eventually will release r_2, which wakes up t_3

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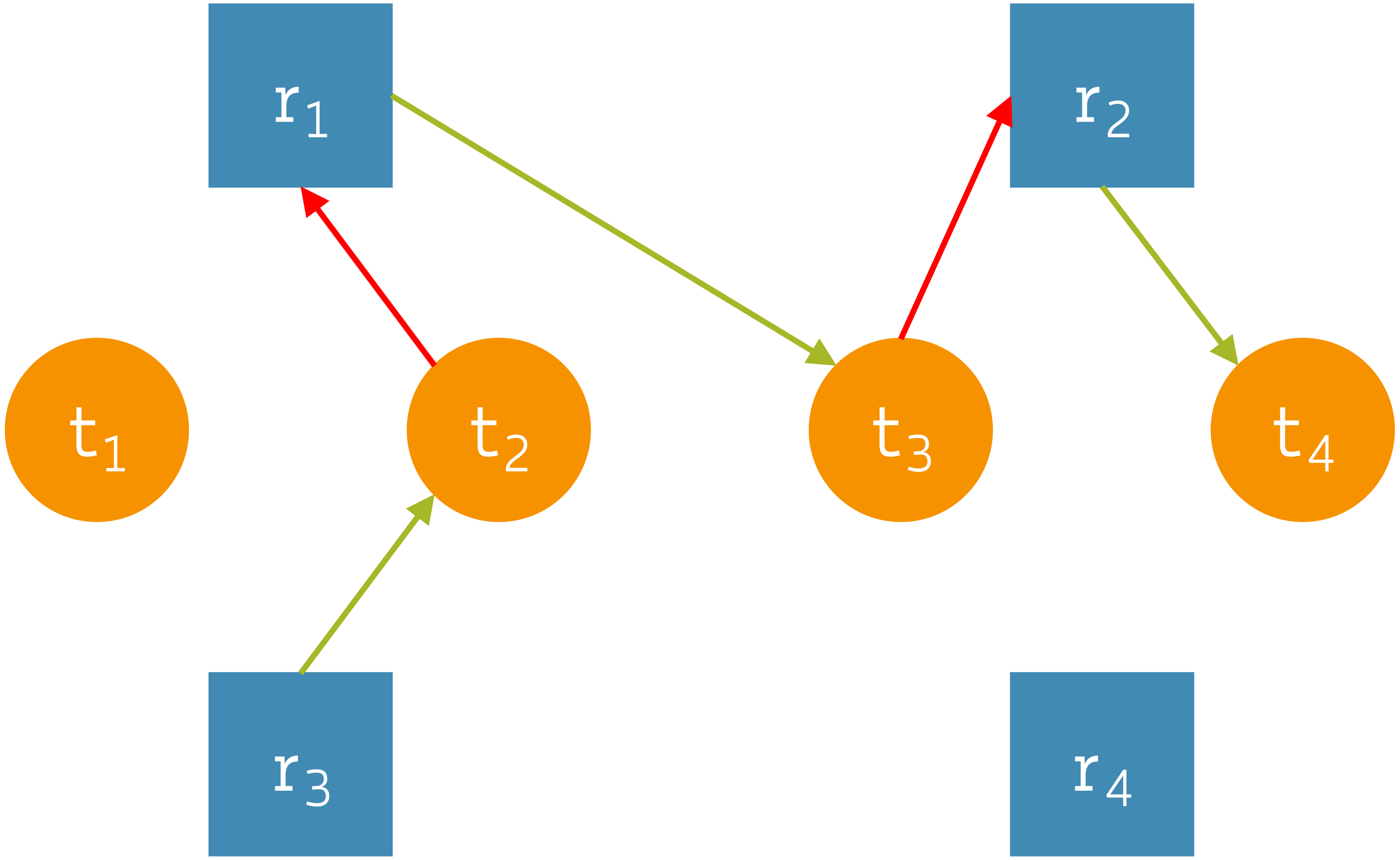

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And so on and so forth…

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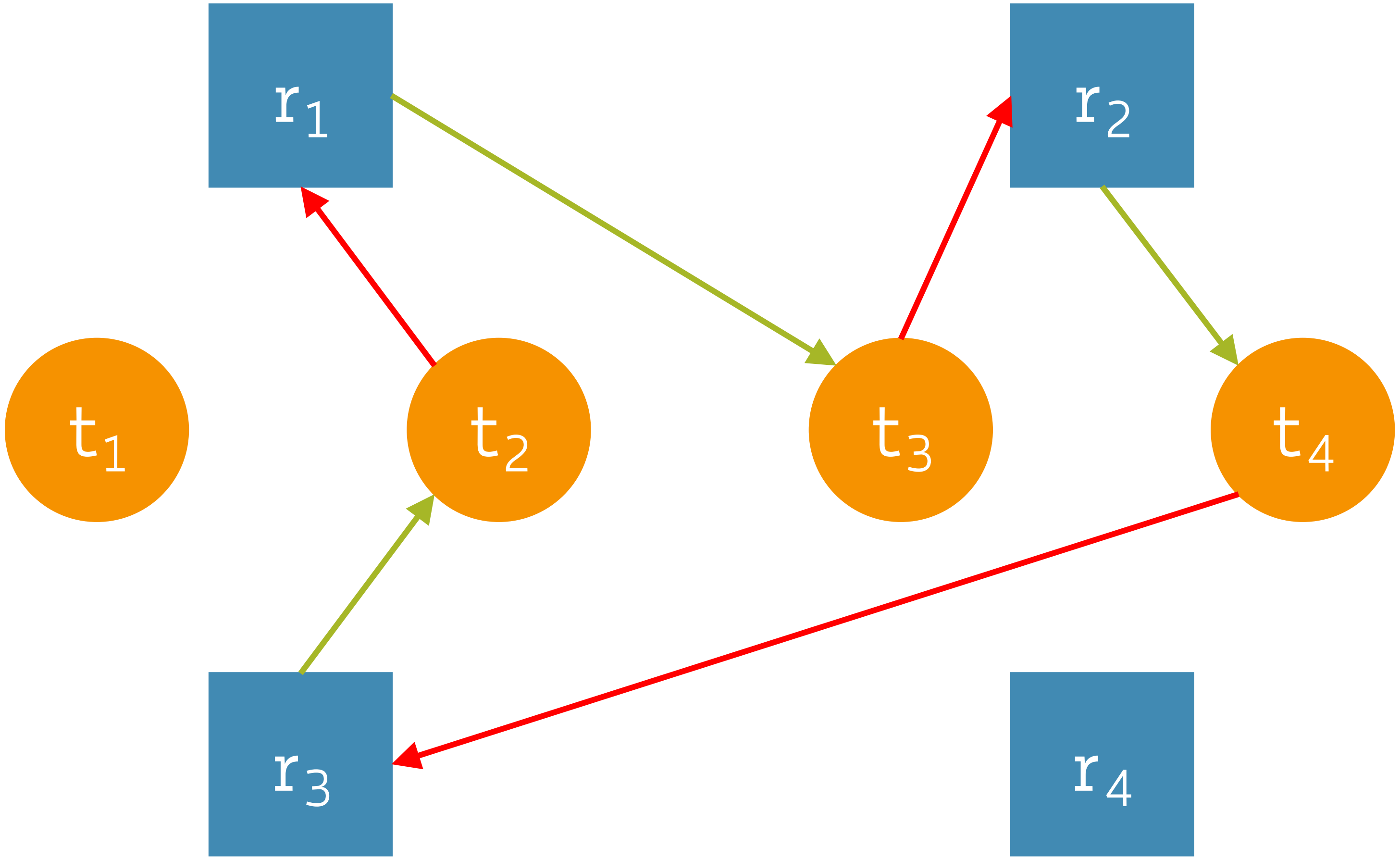

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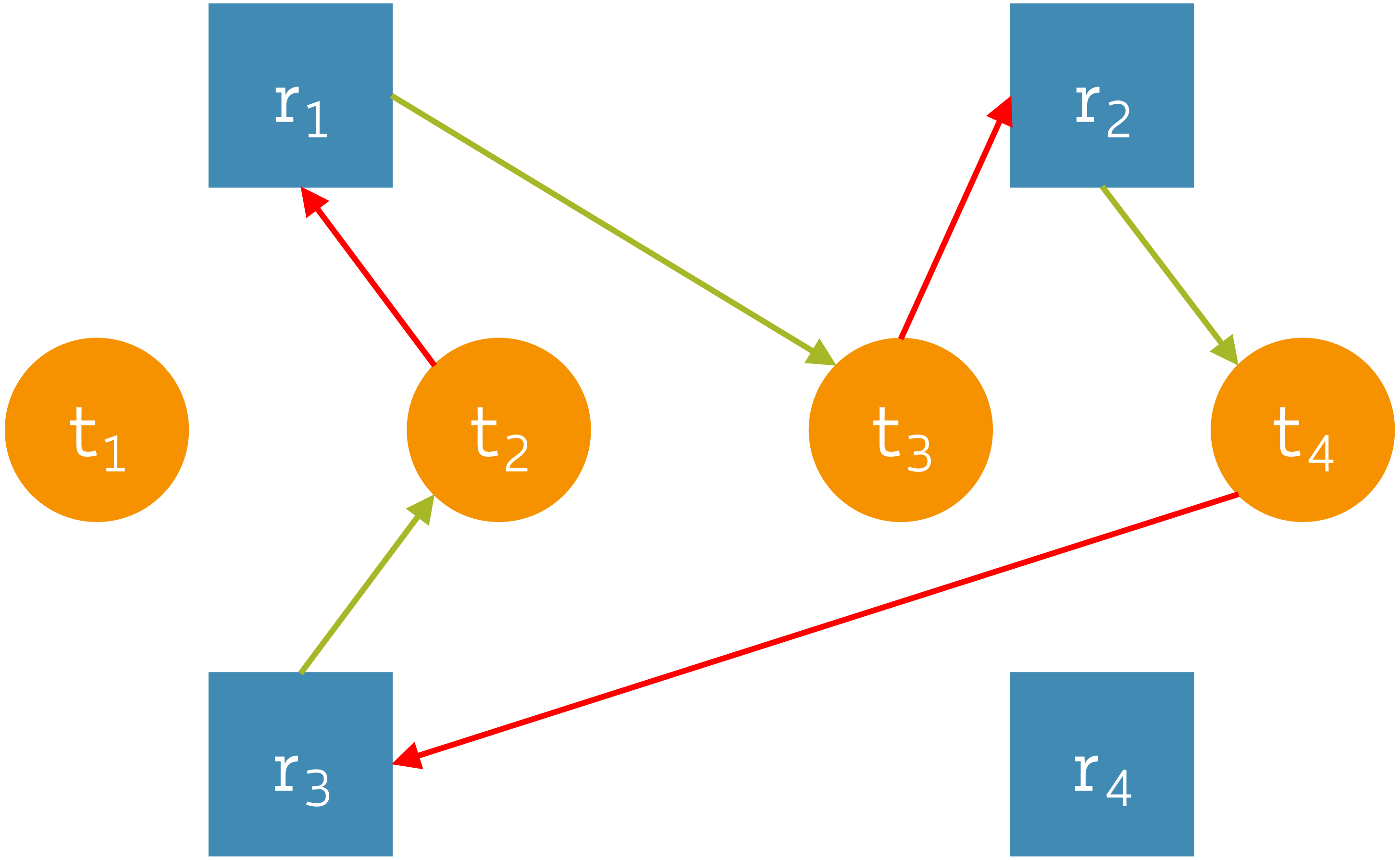

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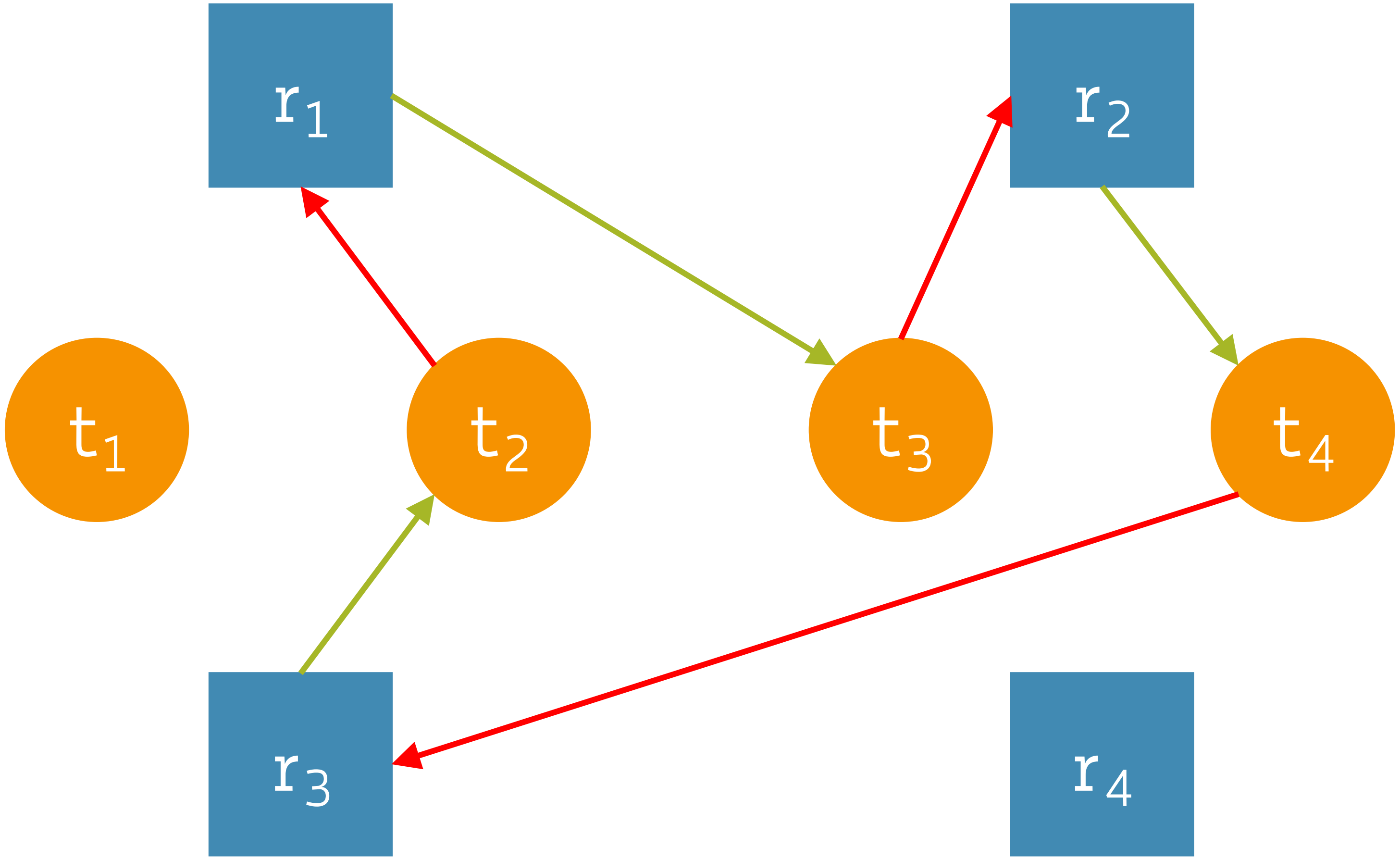

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We are assuming the multiplicity of each resource is 1 (i.e., one r_1, one r_2, etc.)

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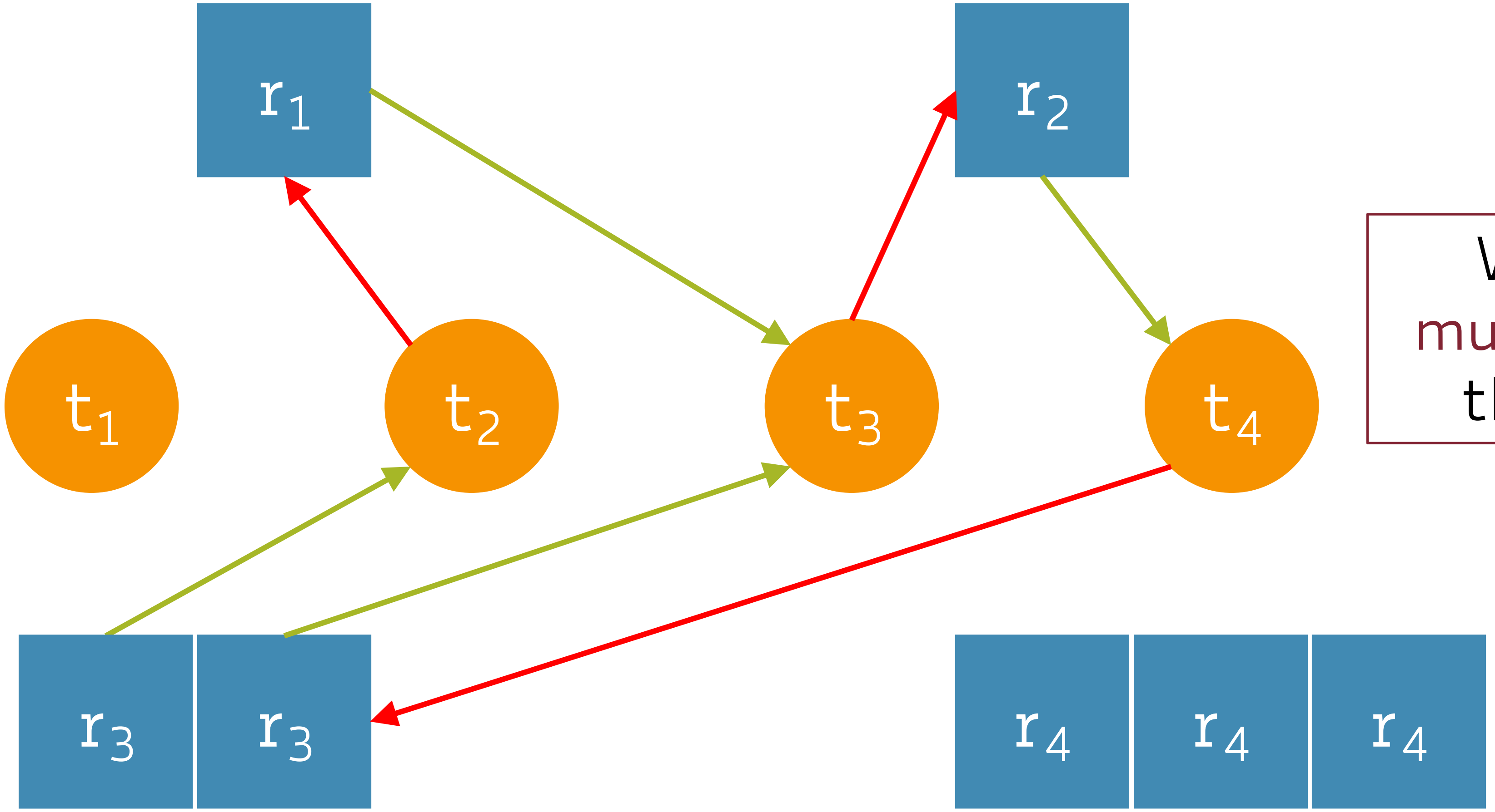

What if there are multiple instances of the same resource?

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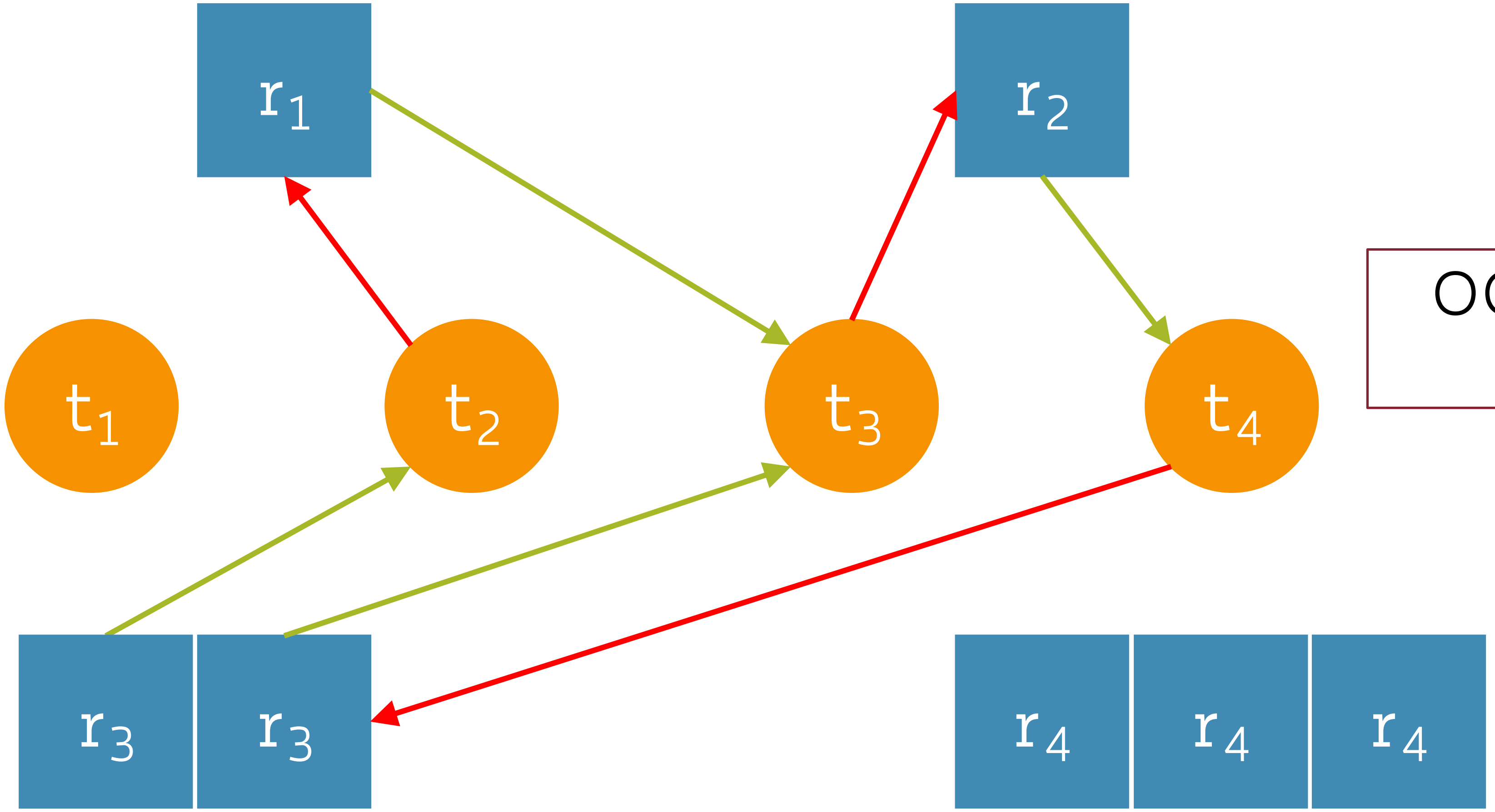
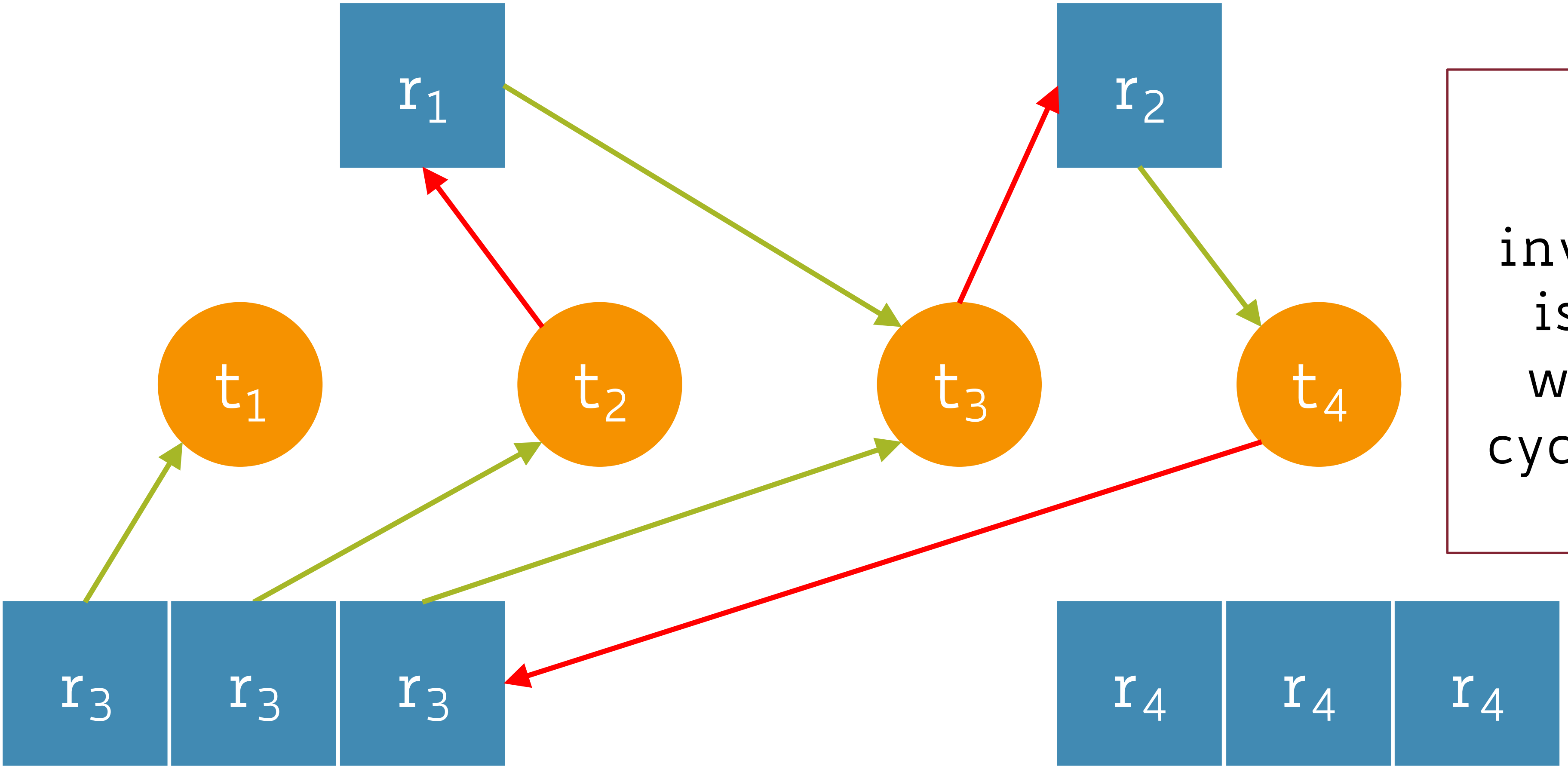


OOPS! This is still a deadlock

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 $|V|$ = #threads + #resources

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Deadlock: Detect and Correct It!

- When to run such a detection algorithm?
  - Before granting a resource → each granted request will take $O(|V|^2)$

Deadlock: Detect and Correct It!

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Deadlock: Detect and Correct It!

- 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

Our Journey

- What is deadlock?
- Conditions for deadlock to happen
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Deadlock Avoidance: Resource Reservation

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

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$$m_i = \textit{maximum} \text{ number of resources that thread } i \textit{ might} \text{ request}$$
$$c_i = \textit{current} \text{ number of resources that thread } i \text{ is holding}$$
$$C = \sum_{i=1}^{n} c_i = \textit{total} \text{ number of resources currently allocated}$$
$$R = \textit{maximum} \text{ number of resources overall available}$$

Deadlock Avoidance: Resource Reservation

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$$
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R &= \textit{maximum} \text{ number of resources overall available}
\end{aligned}
$$

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

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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)

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t_1	4	3	1
t_2	8	4	4
t_3	12	4	8

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Is the current state safe?

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

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

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

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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)

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

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)

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 resource allocation graph

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

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

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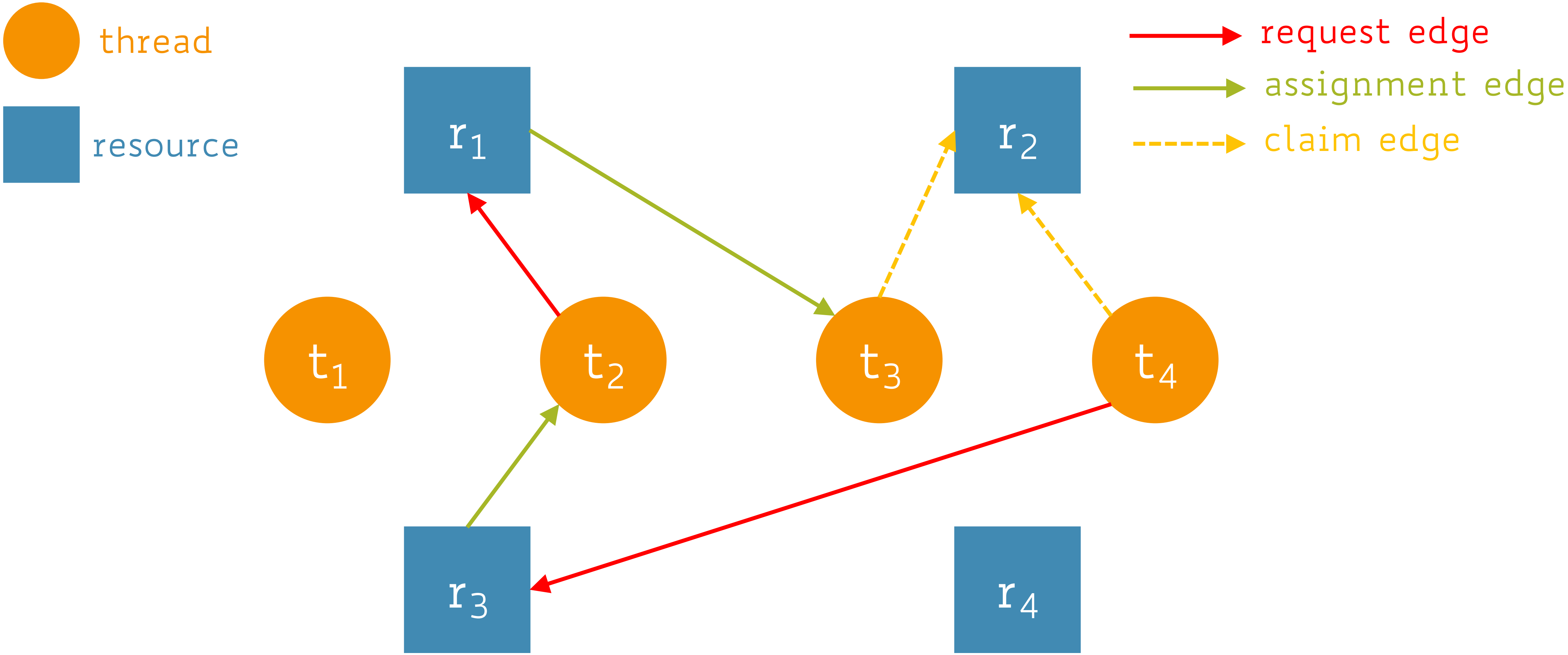
- In other words, the claim edge is converted into a request edge and the thread will wait

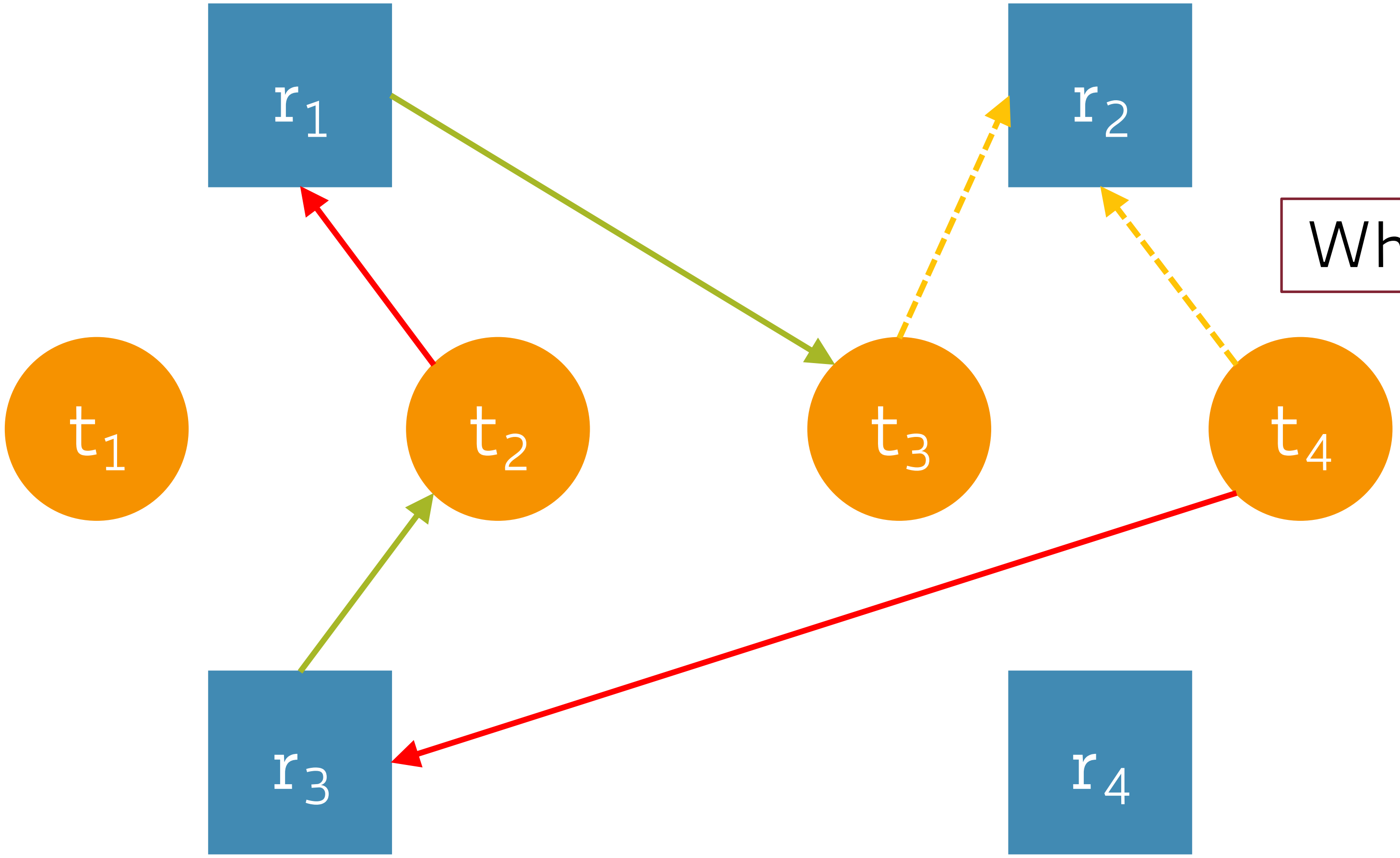
Deadlock Avoidance: Resource Allocation Graph

- 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

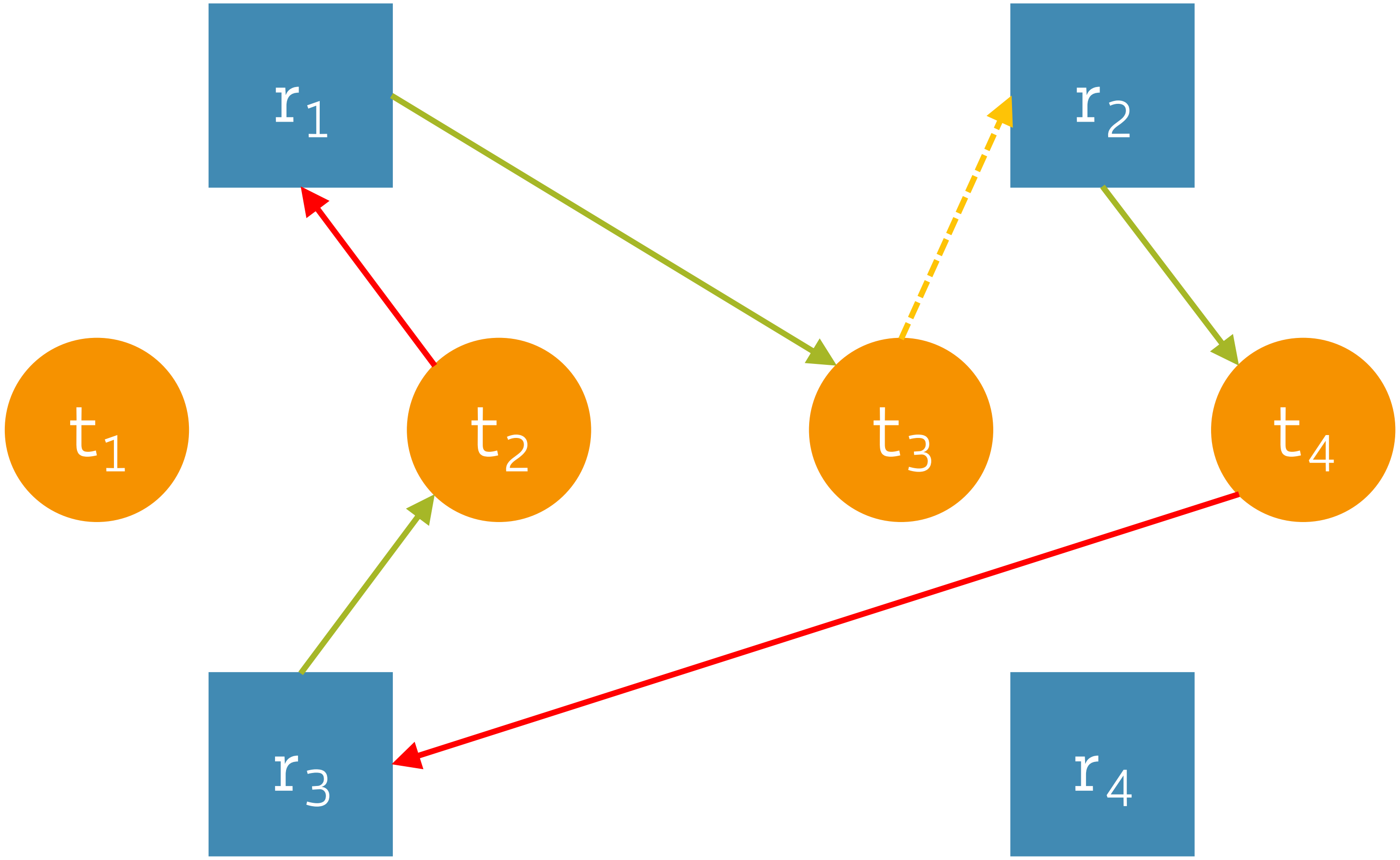


Deadlock Avoidance: Resource Allocation Graph



What happens if t_4 is given r_2?

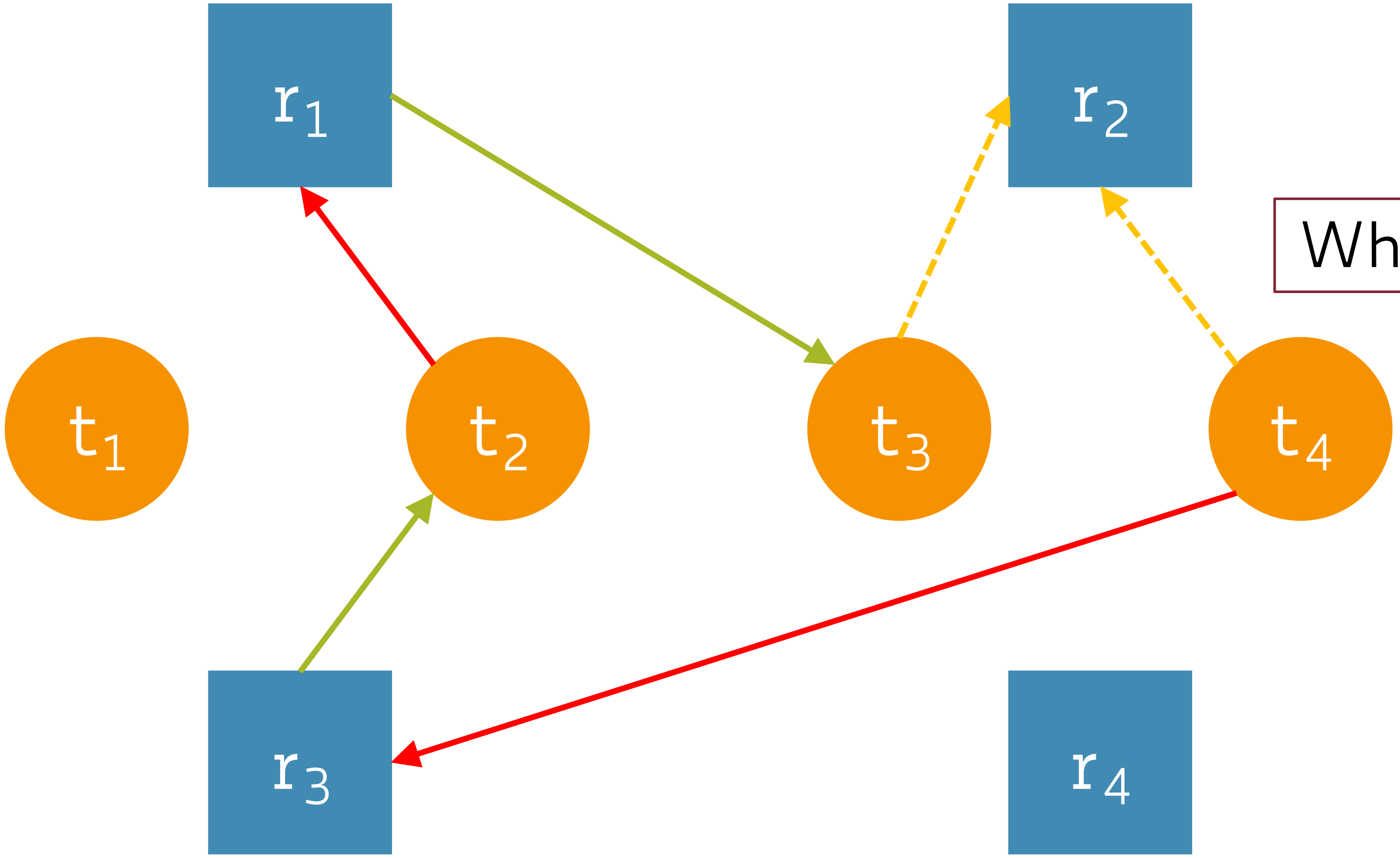
Deadlock Avoidance: Resource Allocation Graph



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

unsafe state

Deadlock Avoidance: Resource Allocation Graph



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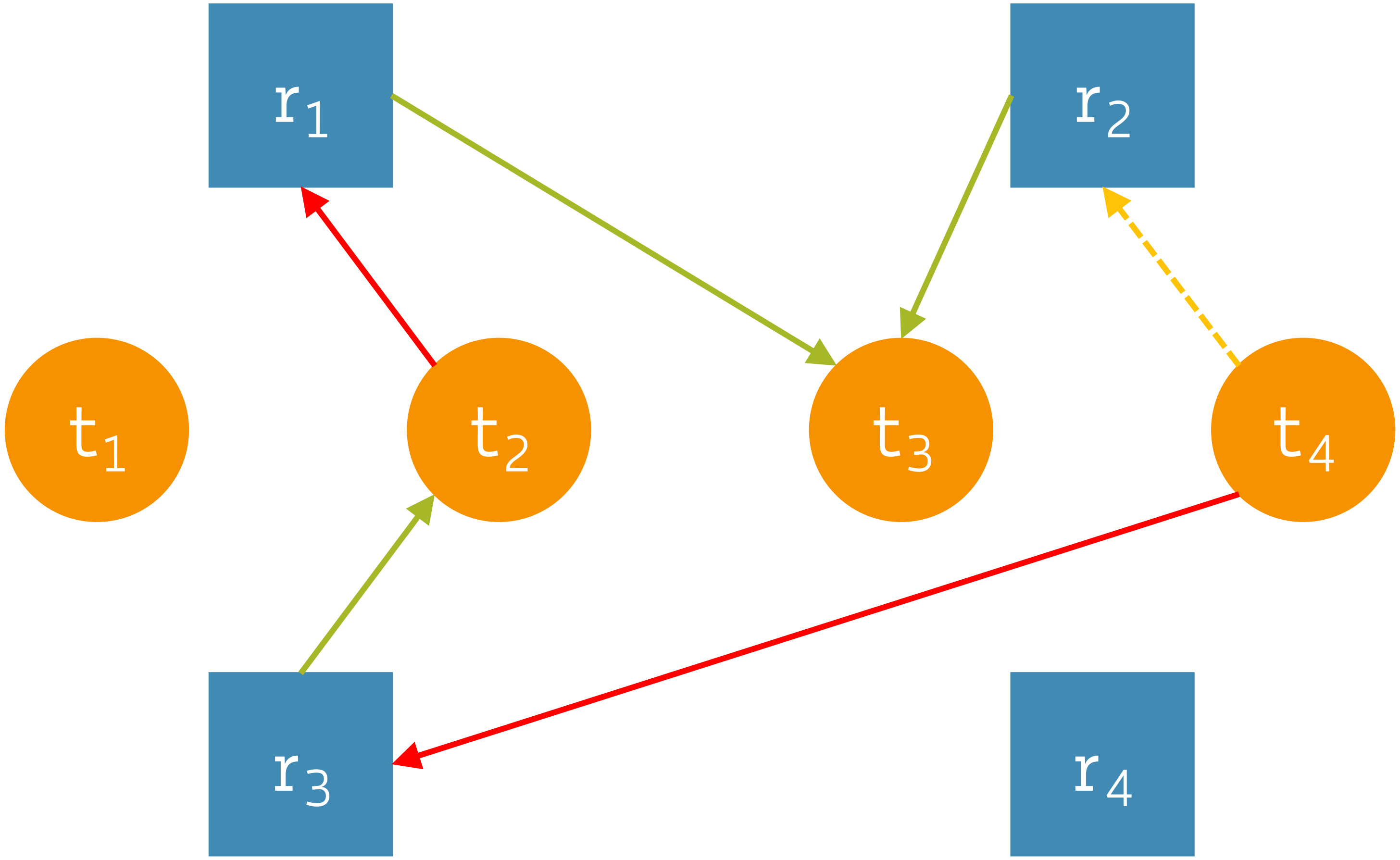
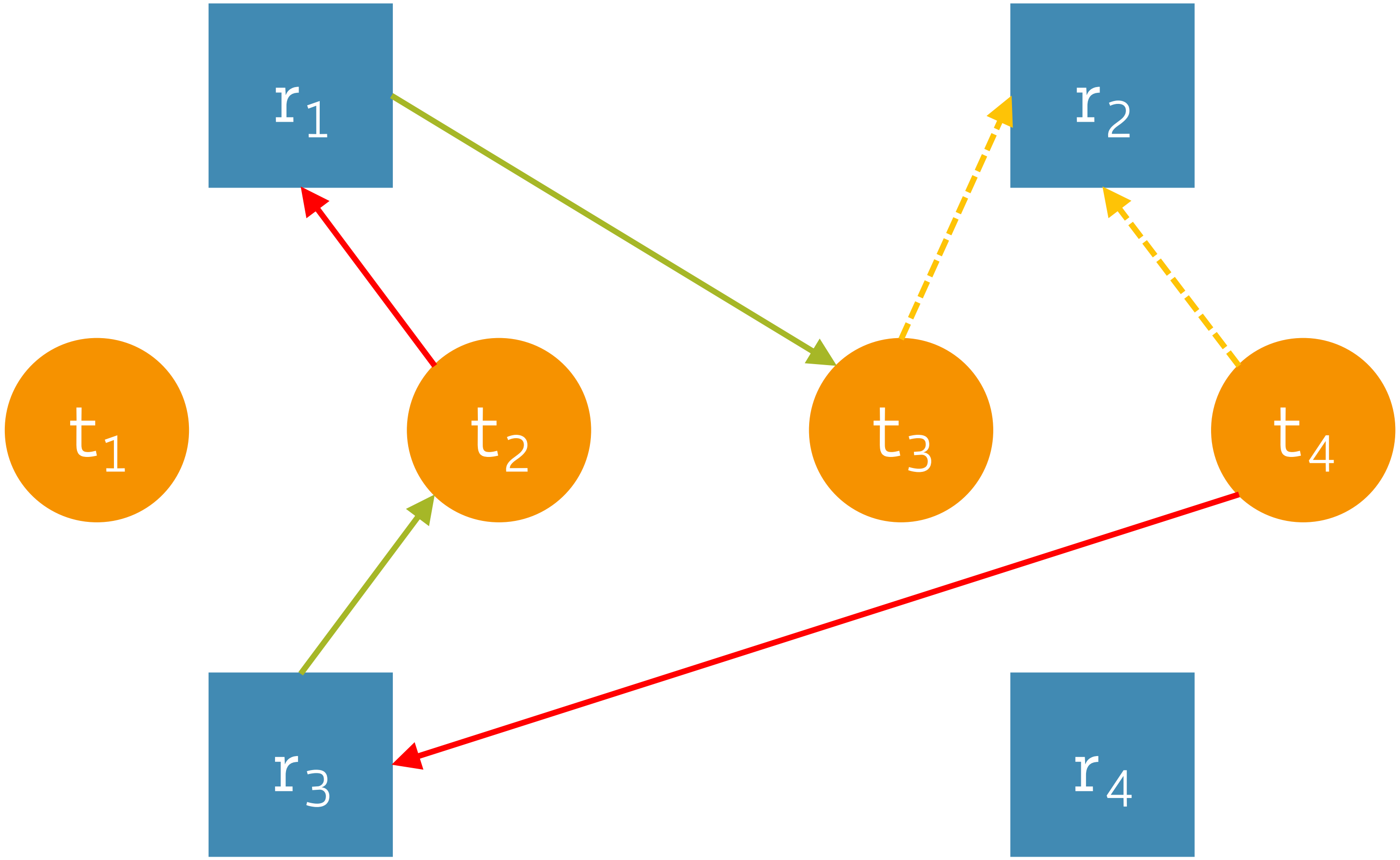


We are not introducing any potential cycle (t_4 requests r_2)

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 x m matrix
  - max[i, j] = k means thread i may require at most k resources of type j
- allocation[1..n, 1..m]: n x m matrix
  - allocation[i, j] = k means thread i has allocated k resources of type j
- need[1..n, 1..m]: n x 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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  - 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 tasks 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 that 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
THREADS	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
THREADS	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											
		MAX			ALLOCATION			AVAILABLE			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	T_0	0	0	1	0	0	1						
	T_1	1	7	5	1	0	0						
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		RESOURCES									NEED		
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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						
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		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	T_0	0	$\boxed{0}$	1	0	$\boxed{0}$	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						
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		RESOURCES									NEED		
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	T_0	0	0	$\boxed{1}$	0	0	$\boxed{1}$				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			

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		MAX			ALLOCATION			AVAILABLE			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
	A	B	C	A	B	C	A	B	C	A	B	C
THREADS 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			NEED		
	A	B	C	A	B	C	A	B	C	A	B	C
THREADS 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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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 <= NEED and b. REQUEST <= AVAILABLE

		RESOURCES									NEED		
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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? YES! (0, 5, 2) <= (0, 7, 5)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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 <= AVAILABLE?

		MAX			ALLOCATION			AVAILABLE			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			

RESOURCES: MAX, ALLOCATION, AVAILABLE

Banker's Algorithm: Example

1.b. REQUEST <= AVAILABLE? YES! (0, 5, 2) <= (1, 5, 2)

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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
THREADS	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
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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			NEED		
		A	B	C	A	B	C	A	B	C	A	B	C
THREADS	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