

Systems and Networking I

Applied Computer Science and Artificial Intelligence
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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

Our Journey

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

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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

What is Deadlock?

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

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Thread A

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

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

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

Thread B

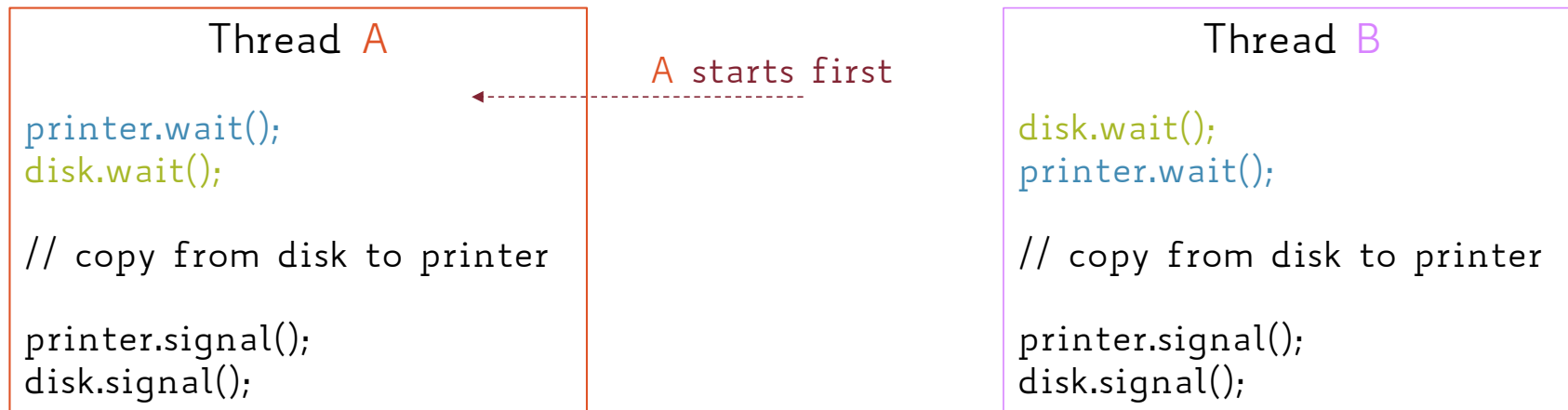
```
disk.wait();  
printer.wait();
```

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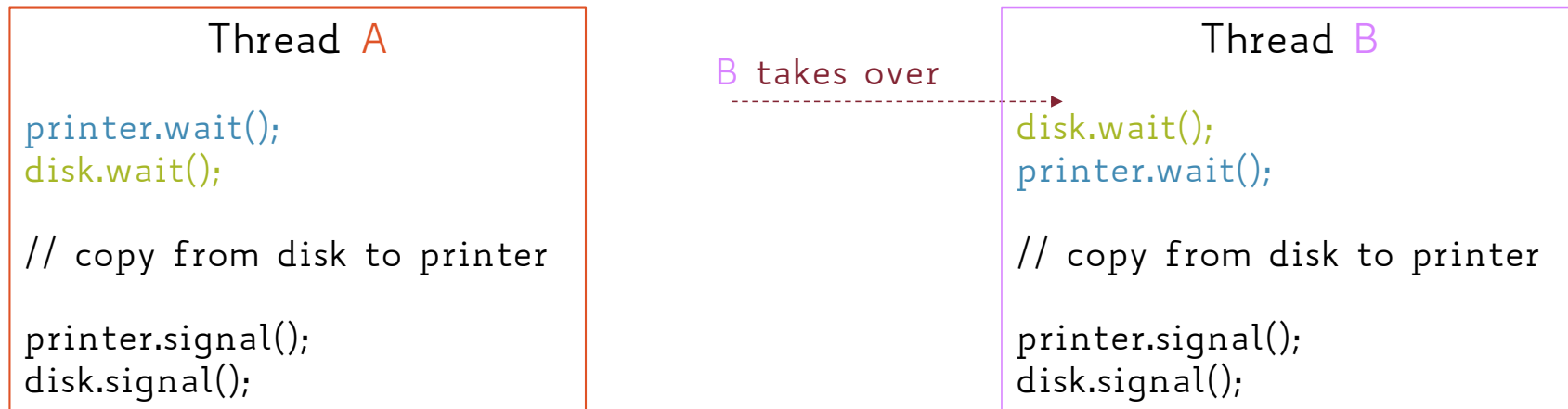
```
printer.wait(); Acquires printer and context switch  
disk.wait();  
  
// copy from disk to printer  
  
printer.signal();  
disk.signal();
```

Thread B

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

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Acquires disk and
context switch

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Thread A

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

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

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

A executes again and blocks



Thread B

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

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

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

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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();
```

B executes again and blocks

What is Deadlock?

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

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

// copy from disk to printer

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printer.signal();  
disk.signal();
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Thread B

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

// copy from disk to printer

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

A waits B to release the disk

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```
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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();
```

B waits A to release the printer

Deadlock: Terminology

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- **Deadlock avoidance (online)**: scheduling threads to avoid deadlocks
- **Deadlock detection (online)**: finds instances of deadlocks and tries to recover

Deadlock vs. Starvation

- Not to be confused with each other!

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Deadlock vs. Starvation

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

Our Journey

- What is deadlock?
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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 circular chain of waiting threads t_1, \dots, t_n where t_i holds a resource requested by $t_{(i+1)\%n}$

Our Journey

- What is deadlock?
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- **Deadlock prevention**
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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 a lock when it requests another
 - Acquire all locks at once, atomically
 - Use a global lock that wraps the acquisition of all locks
 - Hard to predict all the resources a thread will need and inefficient!

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
 - Some thread libraries allow "trying" acquiring multiple locks
 - Not all resources can be easily preempted (e.g., printers)

Deadlock Prevention

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

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Deadlock Avoidance via Scheduling

- An alternative to statically preventing deadlock upfront

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Deadlock Avoidance via Scheduling

- An alternative to statically preventing deadlock upfront
- Avoidance requires some global knowledge of which locks various threads can grab
- Based on that knowledge, the OS will schedule threads to guarantee that no deadlock occurs
- Can be used only in limited environments where one has full knowledge of all tasks and locks needed

Deadlock Avoidance: Example

- 4 threads: T_1 , T_2 , T_3 , T_4
- 2 CPUs: CPU_1 , CPU_2
- **knowledge:** T_1 grabs locks L_1 and L_2 (in some order)
 T_2 grabs locks L_1 and L_2 (in some order)
 T_3 grabs locks L_2
 T_4 grabs no locks

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A smart scheduler can avoid deadlock by not running T_1 and T_2 in parallel

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T_3 and T_1 (T_2) can run in parallel

Deadlock Avoidance: Safe State

- There exists **at least one** sequence of execution (safe sequence)

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- Grant a resource to a thread if the new state is safe, otherwise make it wait even if the resource is available

Deadlock Avoidance: Safe State

- There exists **at least one** sequence of execution (safe sequence)
- Each thread can obtain all the resources it needs, complete its execution, and release the resources
- An unsafe state does not necessarily mean deadlock (i.e., some threads may not request all the resources they declared)
- Grant a resource to a thread if the new state is safe, otherwise make it wait even if the resource is available
- Given n threads, the naïve, brute-force approach would require analyzing **all the possible permutations** of them $O(n!)$

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: Idea

- Keep track of which threads can finish given the current available resources

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- Repeat the process until:
 - all processes can finish (\rightarrow **safe state**), or
 - no remaining process can finish (\rightarrow **unsafe state**)

Banker's Algorithm: Idea

- Keep track of which threads can finish given the current available resources
- Whenever one thread that can finish is found, pretend it finishes and releases its resources
- Repeat the process until:
 - all processes can finish (\rightarrow **safe state**), or
 - no remaining process can finish (\rightarrow **unsafe state**)
- This solution ensures that if any safe sequence exists, one will be found **without needing to test all permutations**

Banker's Algorithm: Data Structures

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

Banker's Algorithm: Pseudocode

```
work = available                      // m-dimensional vectors
finish[i] = false for all i

repeat                                // outer loop
    found = false
    for i in 1..n:                    // inner loop
        if not finish[i] and need[i] <= work:
            work = work + allocation[i]
            finish[i] = true
            found = true
    until not found

if all finish[i] == true // safe state
    return true
return false                // unsafe state
```

Banker's Algorithm: Time Complexity

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            finish[i] = true
            found = true
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    return true
return false              // unsafe state
```

The **inner loop** scans all n threads to look for one that can finish $\rightarrow O(n)$

Banker's Algorithm: Time Complexity

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if all finish[i] == true // safe state
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return false              // unsafe state
```

The **outer loop** runs as long as we find at least one process that can finish.

In the worst case, finding and completing only one thread at each iteration $\rightarrow O(n)$

Banker's Algorithm: Time Complexity

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Checking $\text{need}[i] \leq \text{work}$ may
require up to m resource types \rightarrow
 $O(m)$ per thread

Banker's Algorithm: Time Complexity

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return false              // unsafe state
```

Overall,
 $O(n^2*m)$

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

Banker's Algorithm: Example

Q2: What is the content of the NEED matrix?

		RESOURCES											
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	0	0	1						
	T ₁	1	7	5	1	0	0						
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$$NEED[i, j] = MAX[i, j] - ALLOCATION[i, j]$$

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

T_2 eventually finishes and releases all its resources

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

T_3 eventually finishes and releases all its resources

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

1.a. REQUEST \leq NEED?

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

1.b. REQUEST \leq AVAILABLE?

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

Let's start with T_0

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

Banker's Algorithm: Example

Eventually, T_0 finishes and releases all its resources

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

T_2 eventually finishes and releases all its resources

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

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

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

Banker's Algorithm: Example

T_3 eventually finishes and releases all its resources

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

Banker's Algorithm: Example

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

		RESOURCES									NEED		
		MAX			ALLOCATION			AVAILABLE					
		A	B	C	A	B	C	A	B	C	A	B	C
T H R E A D S	T ₀	0	0	1	-	-	-				-	-	-
	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			

Our Journey

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

Deadlock Detection: Resource Allocation Graph

- We define a **directed graph** $G=(V, E)$ where:

Deadlock Detection: Resource Allocation Graph

- We define a **directed graph** $G=(V, E)$ where:
 - V is the set of vertices representing both **resources** $\{r_1, \dots, r_m\}$ and **threads** $\{t_1, \dots, t_n\}$

Deadlock Detection: Resource Allocation Graph

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 - E is the set of edges between resources and threads

Deadlock Detection: Resource Allocation Graph

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 - V is the set of vertices representing both **resources** $\{r_1, \dots, r_m\}$ and **threads** $\{t_1, \dots, t_n\}$
 - E is the set of edges between resources and threads
- Edges can be of **2 types**:

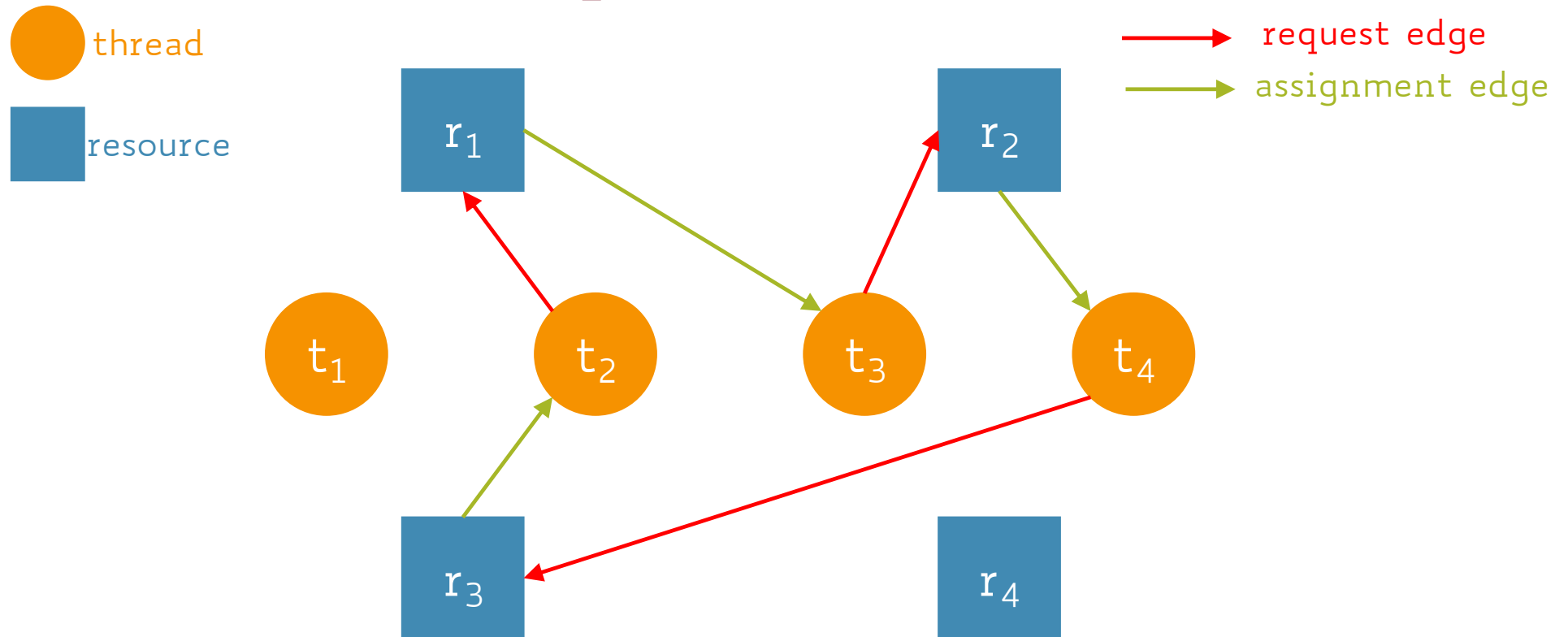
Deadlock Detection: Resource Allocation Graph

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 - E is the set of edges between resources and threads
- Edges can be of **2 types**:
 - **Request Edge** \rightarrow a directed edge (t_i, r_j) indicates that t_i has requested r_j , but not yet acquired

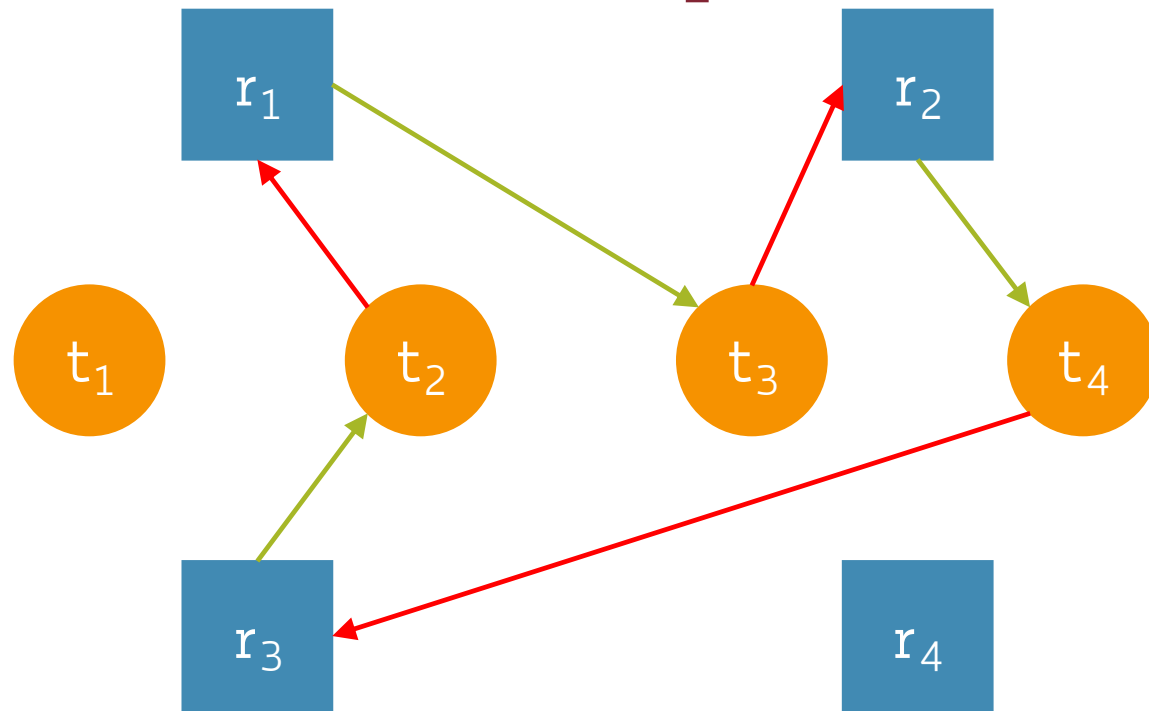
Deadlock Detection: Resource Allocation Graph

- We define a **directed graph** $G=(V, E)$ where:
 - V is the set of vertices representing both **resources** $\{r_1, \dots, r_m\}$ and **threads** $\{t_1, \dots, t_n\}$
 - E is the set of edges between resources and threads
- Edges can be of **2 types**:
 - **Request Edge** \rightarrow a directed edge (t_i, r_j) indicates that t_i has requested r_j , but not yet acquired
 - **Assignment Edge** \rightarrow a directed edge (r_j, t_i) indicates that the OS has allocated r_j to t_i

Deadlock Detection: Resource Allocation Graph

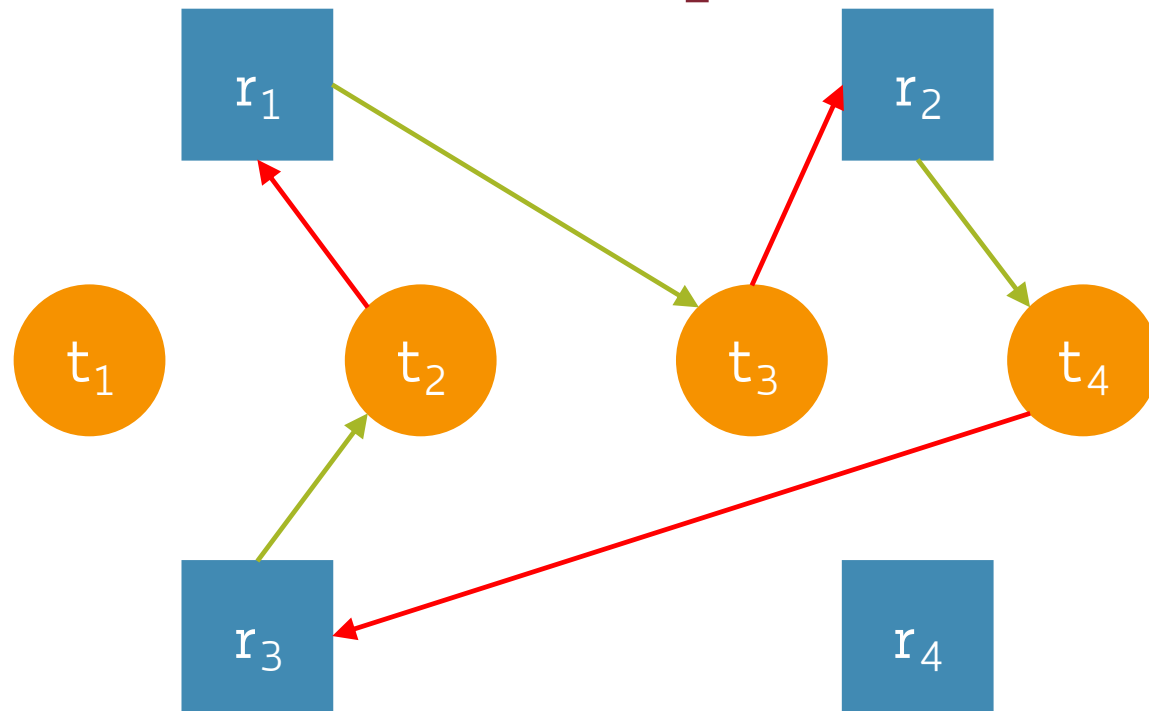


Deadlock Detection: Resource Allocation Graph



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

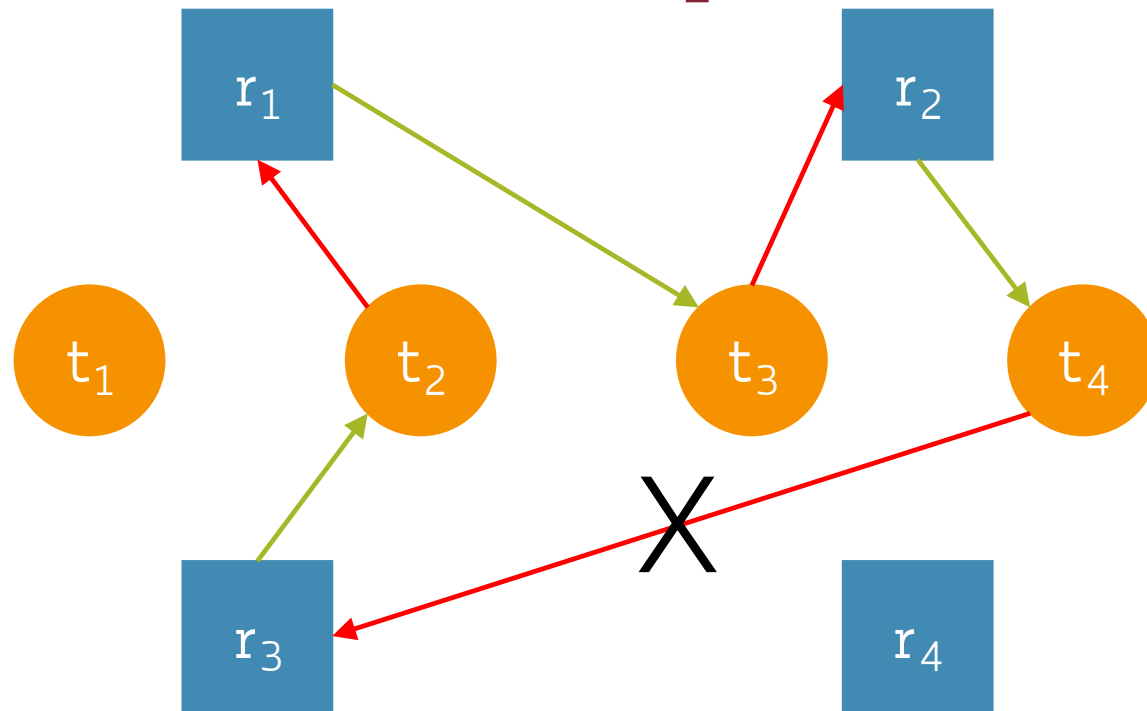
Deadlock Detection: Resource Allocation Graph



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

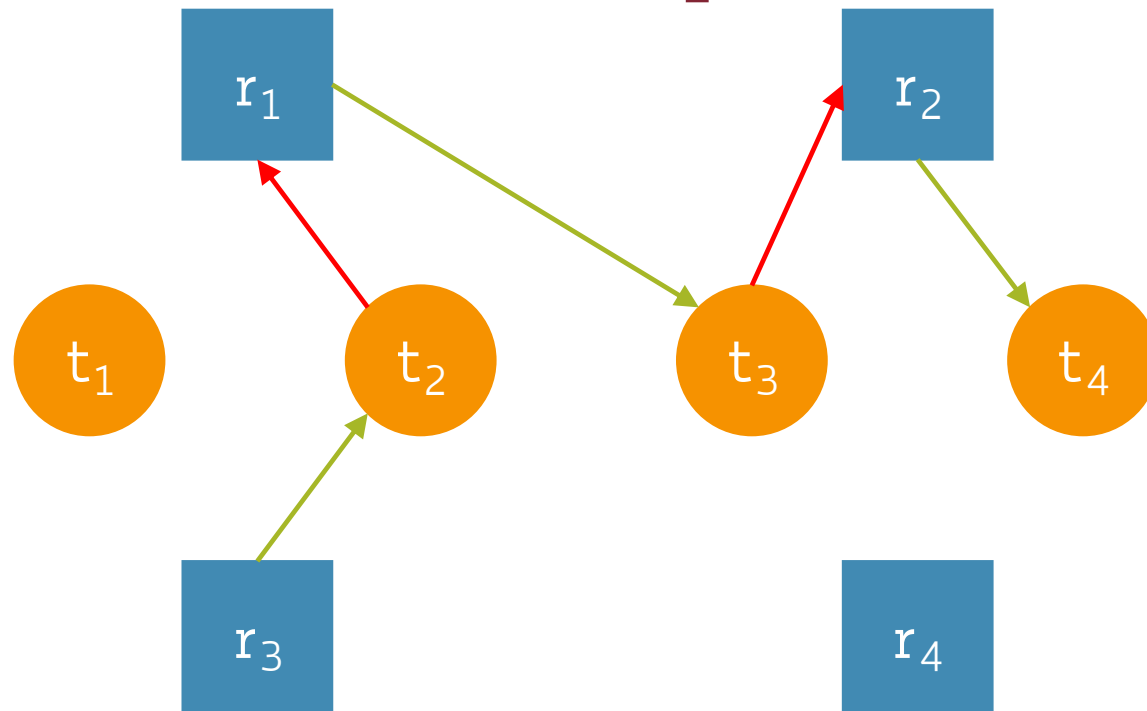
Why?

Deadlock Detection: Resource Allocation Graph



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

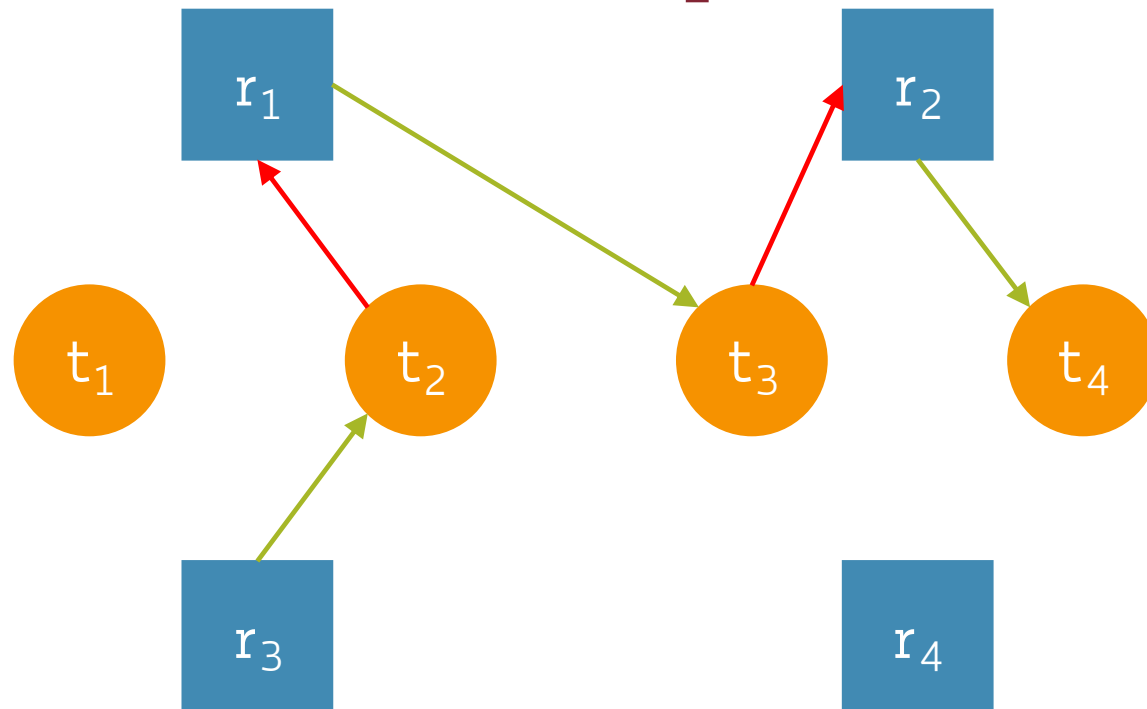
Deadlock Detection: Resource Allocation Graph



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...

Deadlock Detection: Resource Allocation Graph

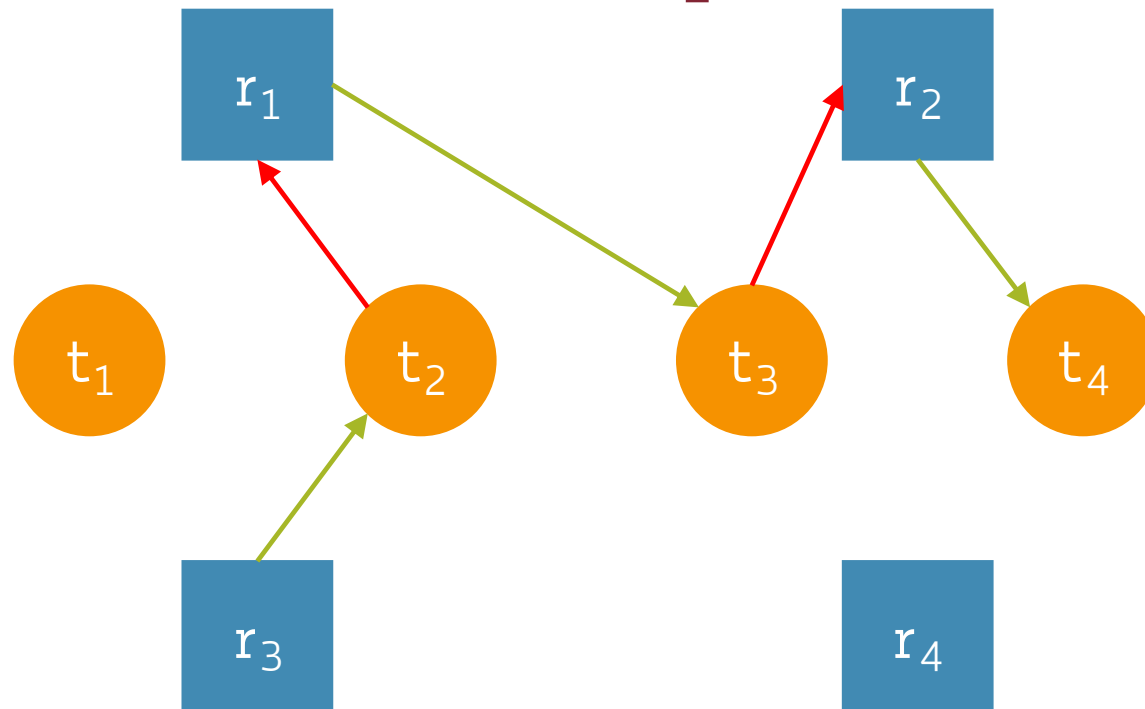


Suppose we remove the edge (t_4, r_3) so as to remove the cycle

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

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

Deadlock Detection: Resource Allocation Graph



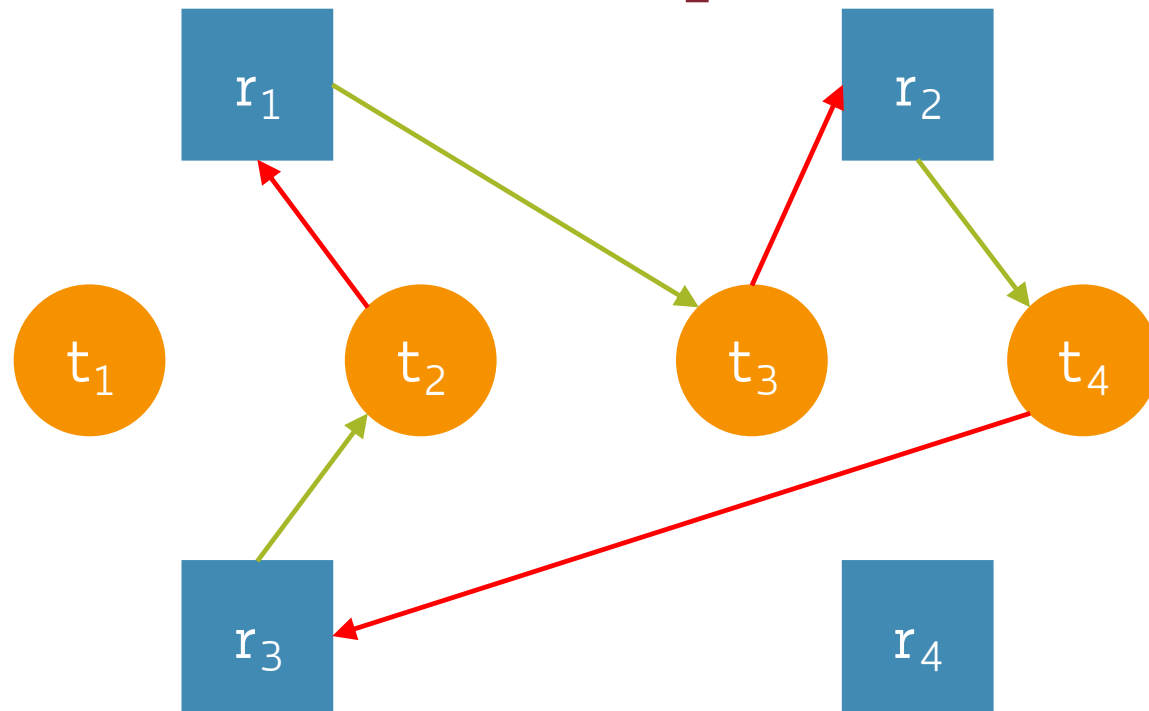
Suppose we remove the edge (t_4, r_3) so as to remove the cycle

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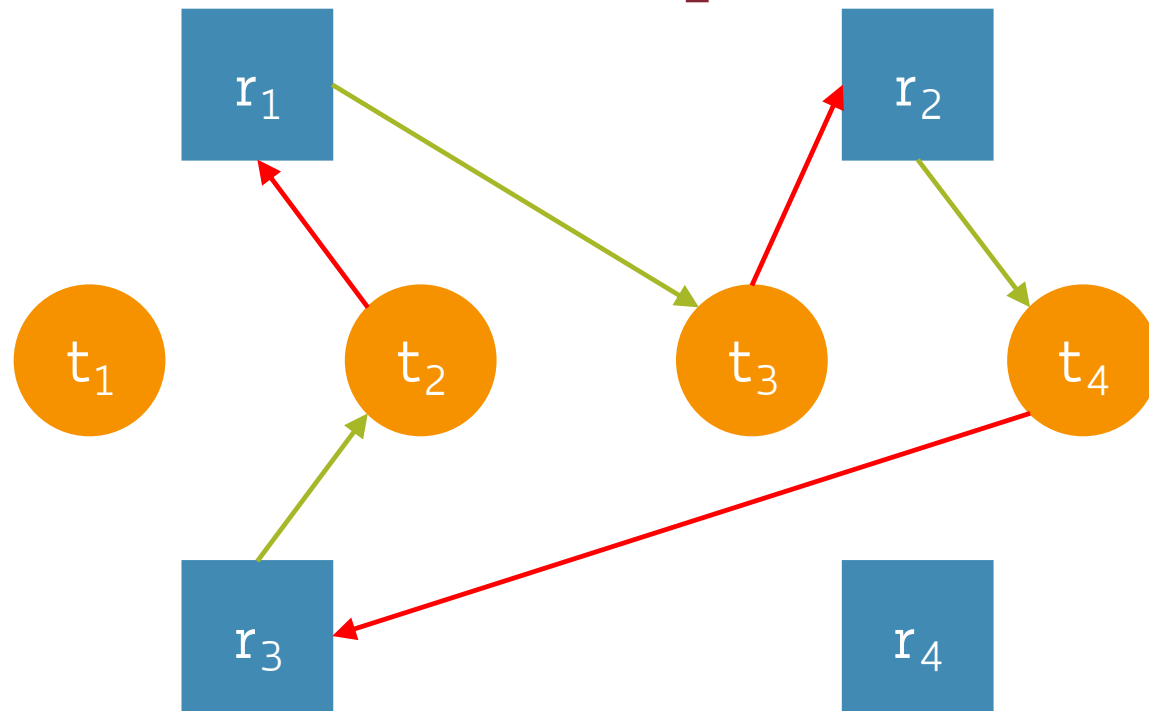
And so on and so forth...

Deadlock Detection: Resource Allocation Graph



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

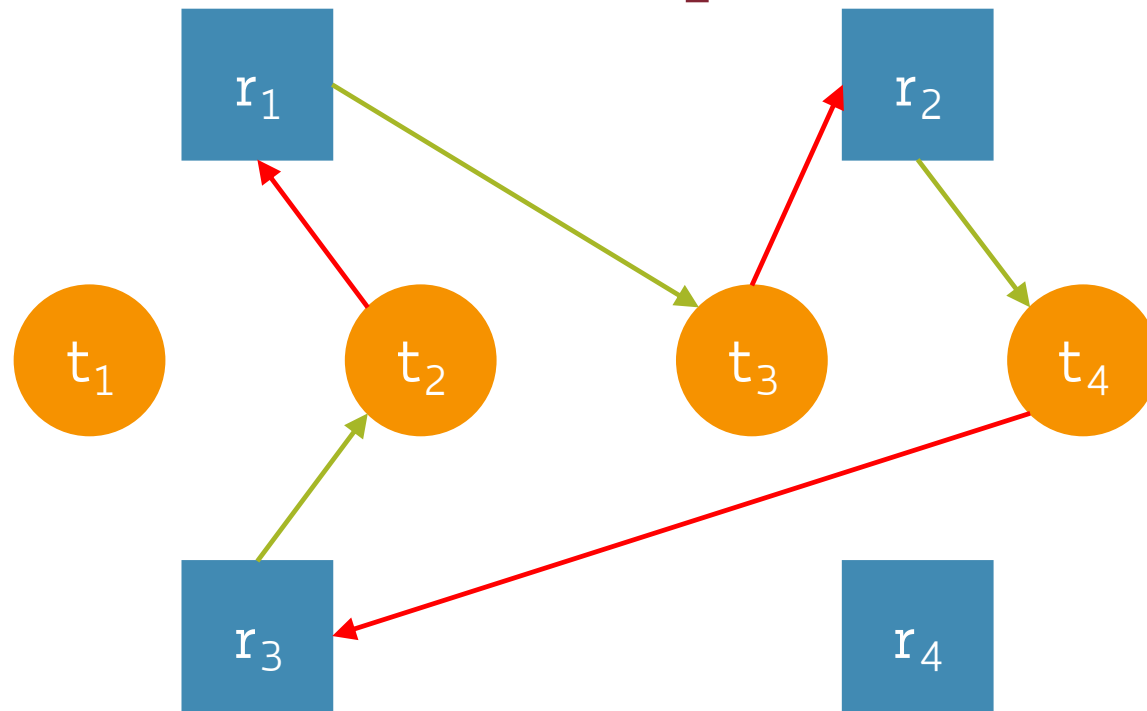
Deadlock Detection: Resource Allocation Graph



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

Why?

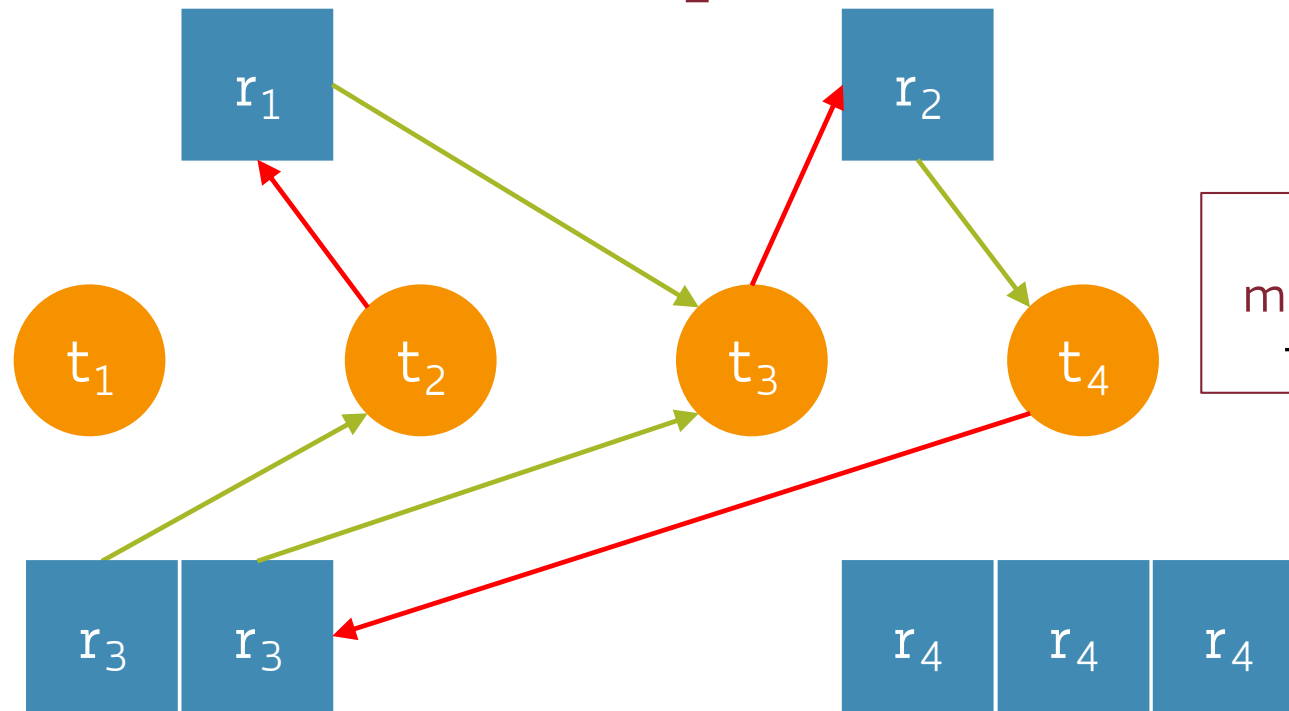
Deadlock Detection: Resource Allocation Graph



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

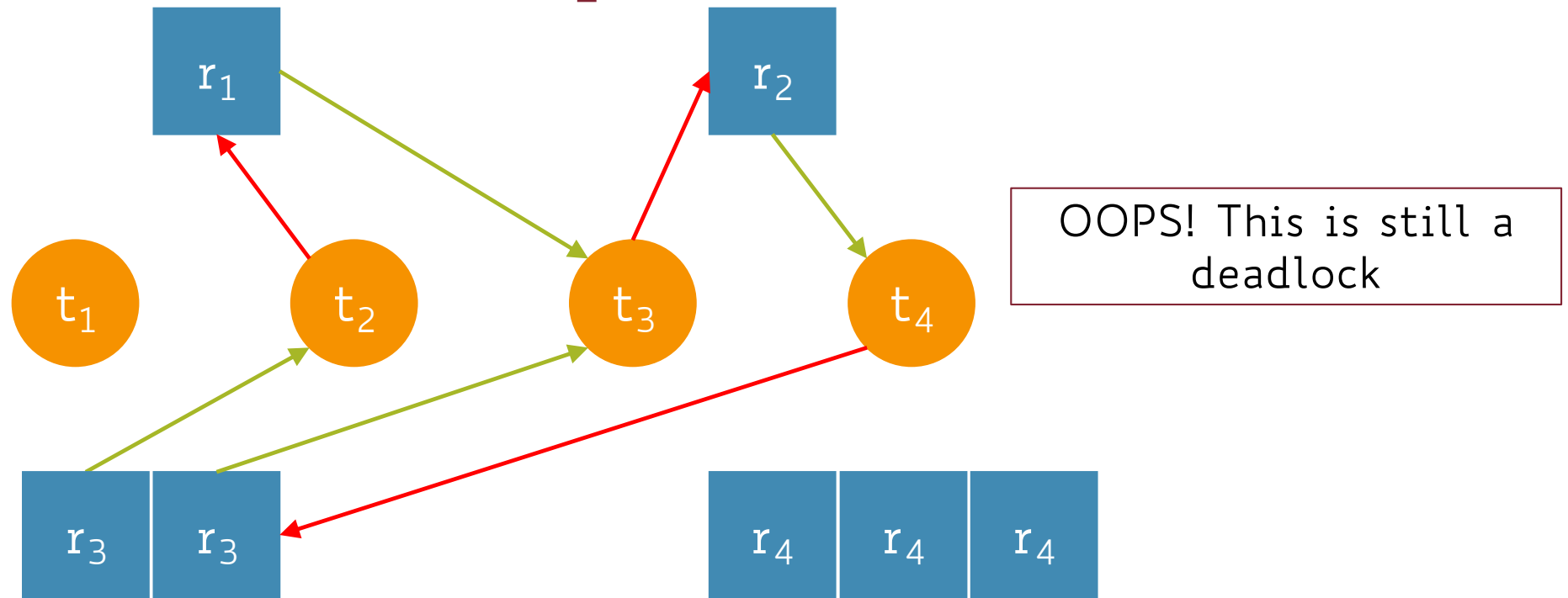
We are assuming the **multiplicity** of each resource is **1** (i.e., one r_1 , one r_2 , etc.)

Deadlock Detection: Resource Allocation Graph

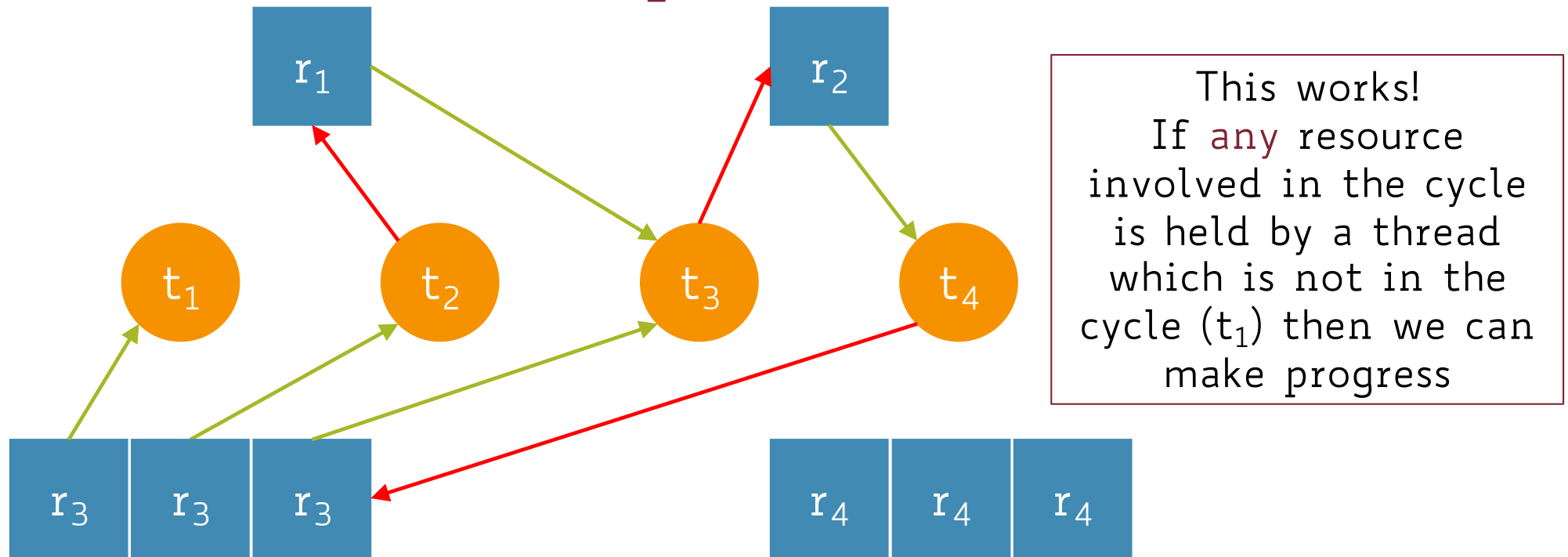


What if there are **multiple** instances of the same resource?

Deadlock Detection: Resource Allocation Graph



Deadlock Detection: Resource Allocation Graph



Deadlock: Detect and Correct It!

- Scan the Resource Allocation Graph (RAG) for cycles, and then break those!

Deadlock: Detect and Correct It!

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- How? Several ways of doing it:

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- How? Several ways of doing it:
 - Kill all the threads in the cycle (quite harsh, ugh?)

Deadlock: Detect and Correct It!

- Scan the Resource Allocation Graph (RAG) for cycles, and then break those!
- 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)

Deadlock: Detect and Correct It!

- Scan the Resource Allocation Graph (RAG) for cycles, and then break those!
- 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)

Deadlock: Detect and Correct It!

- Scan the Resource Allocation Graph (RAG) for cycles, and then break those!
- 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)
- We would like to be more precise than that...

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- $O(|V|+|E|) \sim O(|V|^2)$ as $|E| = O(|V|^2)$ for dense graphs, and $|V| = \text{\#threads} + \text{\#resources}$

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 - On a regular schedule or when the CPU is under-utilized

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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
- **Prevention** → design resource allocation protocols that guarantee at least one of the 4 necessary deadlock conditions never holds
- **Avoidance** → scheduling threads so as to avoid deadlock
- **Detection and Recovery** → recognize deadlock after it has occurred and break it

Summary

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



Summary

After all, if deadlocks are rare, a non-solution like a hard reboot is often the best!

my computer
for no reason



my computer
after a restart

