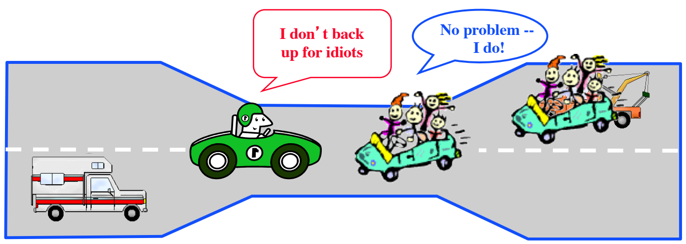
CSCI [4|6]730 Operating Systems

Deadlock

Deadlock Questions?

- What is a deadlock?
- What causes a deadlock?
- How do you deal with (potential) deadlocks?

Deadlock: What is a deadlock?



Deitel & Deitel anecdote

- All entities are waiting for a resource that is **held** by another waiting entity.
  - » Since all are waiting for each other, none can provide any of the things being waited for (they are ALL blocked).
- Simple Example: narrow bridge (resource access to the bridge) --
  - » if a deadlock occurs, resolved if one car backs up

Example (Review): Two Threads?

- Two threads access two shared variables, A and B
  - » Variable A is protected by lock a
  - » Variable B by lock b
- How to add lock and unlock statements?

Does this work?

Time ↓

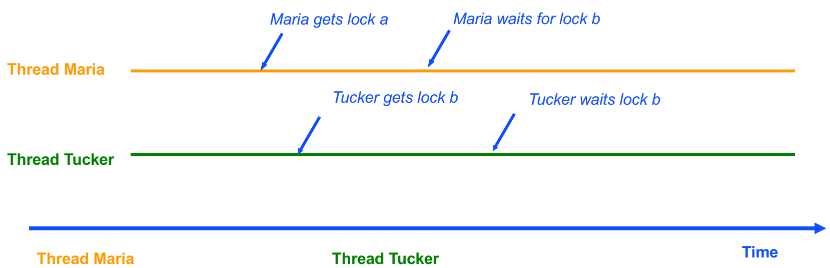
Thread Maria

```
lock(a);
A += 10;
lock(b);
B += 20;

A += B;
unlock(b)
A += 30
unlock(a)
```

Thread Tucker

```
lock(b)
B += 10;
lock(a);
A += 20;

A += B;
unlock(a);
B += 30
unlock(b);
```

Example: Maria & Tucker



Thread Maria

```
lock(a);
A += 10;
lock(b);
B += 20;

A += B;
unlock(b)
A += 30
unlock(a)
```

Waits

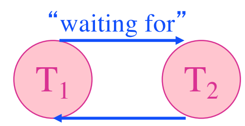
Thread Tucker

```
lock(b)
B += 10;
lock(a);
A += 20;

A += B;
unlock(a);
B += 30
unlock(b);
```

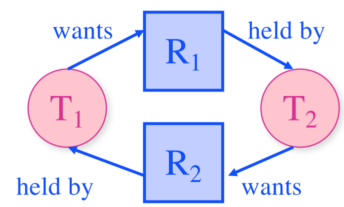

Representing Deadlock

- **Two common ways of representing deadlock:**
  - » **Vertices (circles or rectangles)**
    - – **threads (or processes) in system**
    - – **resources [types] (e.g., locks, semaphores, printers)**
  - » **Edges : indicates either (determined by direction):**
    - – **`waiting for' or `wants' (head of arrow on resource) OR**
    - – **`held by' (head of arrow on thread)**

Wait-For Graph



*Resource Allocation Graph (**RAG**)*



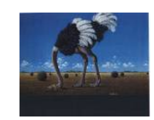
4 Conditions for Deadlock

All four conditions must hold simultaneously

- **Mutual exclusion:**
  - » **Resource cannot be shared**
  - » **Requests are delayed until resource is released**
- **Hold and wait:**
  - » **Thread holds one resource while it waits for another**
- **No preemption:**
  - » **previously granted resources cannot forcibly be taken away**
- **Circular wait:**
  - » **Circular dependencies exist in "waits-for" or "resource-allocation" graphs**
  - » **Each is waiting for a resource held by next member of the chain.**

All four conditions must hold simultaneously

What to do: *Handling Deadlock*



Ostrich algorithm

1. **Ignore**
   - » **Easiest and most common approach (e.g., UNIX).**
2. **Deadlock prevention**
   - » **Ensure deadlock does not happen**
   - » **Ensure at least one of 4 conditions does not occur**
     1. **Hold&Wait, No Preemption, Circularity, Mutual Exclusion**
     2. **System build so deadlock cannot happen**
3. **Deadlock detection and recovery**
   - » **Allow deadlocks, but detect when occur**
   - » **Recover and continue**
4. **Deadlock avoidance**
   - » **Ensure deadlock does not happen**
   - » **Use information about resource requests to dynamically avoid unsafe situations (Thursday)**

Deadlock Prevention

- Mutual exclusion
- Hold and wait
- No preemption
- Circular wait

- Approach
  - » Ensure 1 of 4 conditions cannot occur
  - » Negate each of the 4 conditions
- No single approach is appropriate (or possible) for all circumstancesl
- Examples …

Deadlock Prevention: *Mutual Exclusion*

- **Mutual exclusion**
- Hold and wait
- No preemption
- Circular wait

- No mutual exclusion
- --> Make access to resources **sharable** ;
- Examples: Access to files
  - » Read-only files
  - » Printer daemon needs exclusive access to the printer, there is only one printer daemon -- uses spooling.

Deadlock Prevention *Hold and Wait*

- Mutual exclusion
- ***Hold and wait***
- No preemption
- Circular wait

- Make rules on how a resources hold and requests(waits) on resources
- Two General Approaches:
  1. A Thread only requests resources when it does not hold other resources
     - *release* resources before requesting new ones

Thread Maria

```
lock(a);
A += 10;
unlock(a)
lock(b);
B += 20;
unlock(b)
lock(a)
A += 30
unlock(a)
```

Thread Tucker

```
lock(b)
B += 10;
Unlock(b);
lock(a);
A += 20;
unlock(a);
lock(b)
B += 30
unlock(b);
```


Deadlock Prevention *Hold and Wait*

- Mutual exclusion
- ***Hold and wait***
- No preemption
- Circular wait

- Two Approaches:
  2. Atomically acquire all resources at once (all or none)
     - » **Example**: Single lock to protect all (other variations - e.g., release access to one variable earlier)

Thread Maria

```
lock(AB);
A += 10;
B += 20;
A += 30
unlock(AB)
```

Thread Tucker

```
lock(AB)
B += 10;
A += 20;
B += 30
unlock(AB);
```

Deadlock Prevention
Hold and Wait

Mutual exclusion
Hold and wait
No preemption
Circular wait

- **Summary the Two Approaches:**
  1. **Only request resources when it does not hold other resources**
  2. **Atomically acquire all resources at once**
- **Problems:**
  » **Low resource utilization: ties up resources other processes could be using**
  » **May not know required resources before execution**
  » **Starvation: A thread that need popular resources may wait forever**

Deadlock Prevention
No Preemption

Mutual exclusion
Hold and wait
No preemption
Circular wait

- **Two Approaches:**
  1. **Preempt requestors resource**
     – **Example: B is holding some resources and then requests additional resources that are held by other threads, then B releases all its resources (and start over)**
  2. **Preempt holders resource**
     – **Example: A waiting for something held by B, then take resource away from B and give them to A (B starts over).**
- **Not possible if resource cannot be saved and restored**
  » **Can't take away a lock without causing problems**
- **Only works for some resources (e.g., CPU and memory)**
  » **May cause thrashing.**

Deadlock Prevention
Circular Wait Condition

Mutual exclusion
Hold and wait
No preemption
Circular wait

- **Impose ordering on resources**
  » **Give all resources a ranking or priority; must acquire highest ranked resource first.**
    – **Dijskstra: Establishing the convention that all resources will be requested in order, and released in reverse order,**

Deadlock Detection & Recovery

1. **Allow system to enter deadlock state**
2. **Detection algorithm**
3. **Recovery scheme**

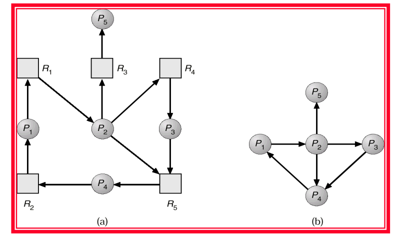
Side Node

- Discovering a deadlock after it occurs, is decidable
- Discovering it ‘before’ it occurs, is in *general* un-decidable: same as the halting problem.

Deadlock *Detection* Single Instance of Each Resource Type

- Maintain a *wait-for* graph (it works on RAGS as well)
  - » Nodes are processes.
  - » Simplify: removes resource nodes and collapse edges
  - » $P_i \rightarrow P_j$ if P_i is waiting for P_j.
- Periodically invoke an algorithm that searches for a cycle in the graph.

Resource Allocation Graphs (RAGs) Wait For



Example Code : A depth first search to find circles

For each node in the graph:

```
L = {empty list} and Nodes = {list of all unvisited nodes};
current node = initial node // pick one randomly
while( current node is not the initial node twice ) then done
     L.enqueue(current node); // add to node to end of L
     if( current node is in L twice )
        there is a cycle ⇒ cycle and return
     if( there is an unmarked arc explore that one )
        mark the arc as visited and use destination as new
           current node
     else // backtrack
        go back to previous node
Back to initial node there is no cycle
```


Deadlock detection

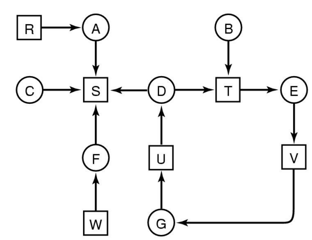
- Do a depth-first-search on the resource allocation graph (RAG)

D, E, G ?

are deadlocked

A, C, F ?

are not deadlocked because S can be allocated to either and then the others can take turn to complete

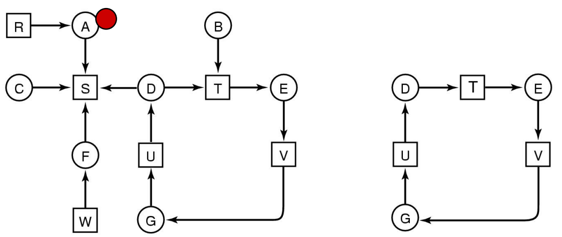


(a)

Example: Deadlock Detection

- **Do a depth-first-search on the resource allocation graph**

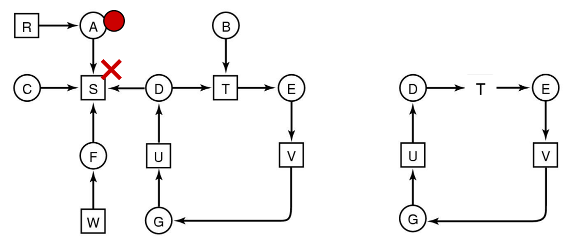
Initialize a list to the empty list, designate arcs as 'unvisited'



(a) (b)

Example: Deadlock Detection

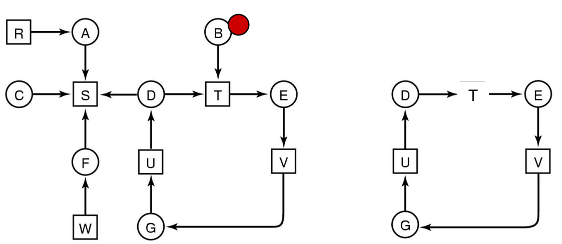
- **Do a depth-first-search on the resource allocation graph**



(a) (b)

Example: Deadlock Detection

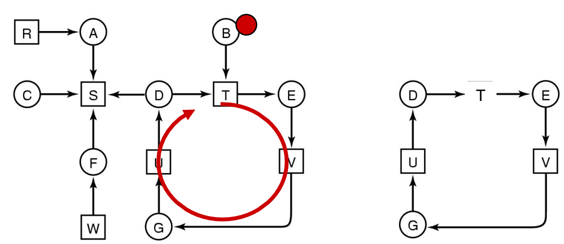
- **Do a depth-first-search on the resource allocation graph**



(a) (b)

Example: Deadlock Detection

- **Do a depth-first-search on the resource allocation graph**

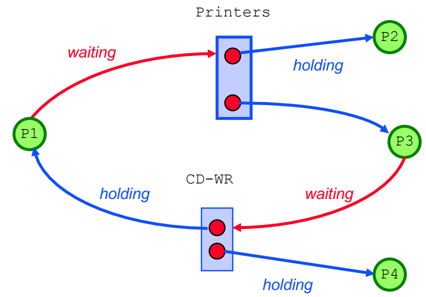


(a) (b)

- What about resources that have multiple resources (e.g., multiple printers)

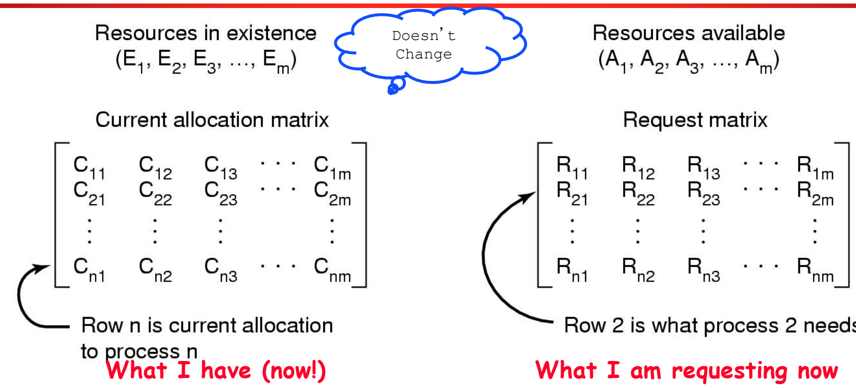
Deadlock Detection with Multiple Resources

- <u>Theorem</u>: *If a graph does not contain a cycle then no processes are deadlocked*
  - » A cycle in a RAG is a <u>necessary</u> condition for deadlock
  - » BUT is it a <u>sufficient</u> condition?



- Next create an algorithm with multiple instances, and its data structures.
  - » Matrices and Vectors each column are numbers available of a particular kind or type, e.g., printers.
  - » Allocation Matrix
  - » Request Matrix
  - » Numbers in Existence Vector
  - » Numbers Available Vector

Deadlock Detection Algorithm: Multiple Resource Instances



$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & \cdots & C_{1m} \\ C_{21} & C_{22} & C_{23} & \cdots & C_{2m} \\ \vdots & \vdots & \vdots & & \vdots \\ C_{n1} & C_{n2} & C_{n3} & \cdots & C_{nm} \end{bmatrix} \qquad \begin{bmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1m} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2m} \\ \vdots & \vdots & \vdots & & \vdots \\ R_{n1} & R_{n2} & R_{n3} & \cdots & R_{nm} \end{bmatrix}$$

- ***Available:*** Indicates the number of available resources of each type (m)
- ***Allocation:*** Number of resources of each type currently allocated (nxm)
- ***Request:*** current requests of each thread (nxm)
  - » If *Request* [i_j] = *k*, then process P_i is requesting *k* more instances of type. R_j.

Example

- **Algorithmic Question**: **Is there a possible allocation sequence of resources so that each process can complete?**

	Tape drives	Plotters	Scanners	CD Roms
E =	4	2	3	1
A =	2	1	0	0

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

Detection algorithm

A **marked** process means it can run to completion

Initially all processes are unmarked.

1. **Look for an unmarked process Pi, whose needs can be satisfied (all):**
   - **the *i*th whole row of R (need) is less than or equal to A(vailable) (i.e, all the resource(s) is/are available)**
2. **If such a process is found, add the i-th row of C(urrently allocated) to A(vailable), mark the process and go back to step 1 (b/c it is done processing and can release its resource)**
3. **If no such process exists the algorithm terminates**

If all marked, no deadlock, o/w deadlocked

Detection algorithm

	Tape drives	Plotters	Scanners	CD Roms
E =	4	2	3	1
A =	2	1	0	0

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

Can we satisfy a ROW in the Request Matrix?

Detection algorithm

	Tape drives	Plotters	Scanners	CD Roms
E =	4	2	3	1
A =	2	1	0	0

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ \boxed{2 \quad 1 \quad 0 \quad 0} \end{bmatrix}$$

Detection algorithm

Tape drives, Plotters, Scanners, CD Roms

E = (4 2 3 1)

Tape drives, Plotters, Scanners, CD Roms

A = (2 1 0 0)

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

Detection algorithm

Tape drives, Plotters, Scanners, CD Roms

E = (4 2 3 1)

Tape drives, Plotters, Scanners, CD Roms

A = (2 1 0 0)

2 2 2 0

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

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Detection algorithm

Tape drives, Plotters, Scanners, CD Roms

E = (4 2 3 1)

Tape drives, Plotters, Scanners, CD Roms

A = (2 1 0 0)

2 2 2 0

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ \cancel{0} & \cancel{1} & \cancel{2} & \cancel{0} \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ \cancel{2} & \cancel{1} & \cancel{0} & \cancel{0} \end{bmatrix}$$

Detection algorithm

Tape drives, Plotters, Scanners, CD Roms

E = (4 2 3 1)

Tape drives, Plotters, Scanners, CD Roms

A = (2 1 0 0)

2 2 2 0

4 2 2 1

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ \cancel{2} & \cancel{0} & \cancel{0} & \cancel{1} \\ \cancel{0} & \cancel{1} & \cancel{2} & \cancel{0} \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ \cancel{1} & \cancel{0} & \cancel{1} & \cancel{0} \\ \cancel{2} & \cancel{1} & \cancel{0} & \cancel{0} \end{bmatrix}$$

Detection algorithm

	Tape drives	Plotters	Scanners	CD Roms
E = (	4	2	3	1)

	Tape drives	Plotters	Scanners	CD Roms
A = (	2	1	0	0)
	2	**2**	**2**	**0**
	4	**2**	**2**	**1**

Current allocation matrix

C =

0	0	1	0
~~2~~	~~0~~	~~0~~	~~1~~
~~0~~	~~1~~	~~2~~	~~0~~

Request matrix

R =

2	0	0	1
~~1~~	~~0~~	~~1~~	~~0~~
~~2~~	~~1~~	~~0~~	~~0~~

No deadlock!

Deadlock detection issues

- **How often should the algorithm run?**
  - » **After every resource request?**
  - » **Periodically?**
  - » **When CPU utilization is low?**
  - » **When we suspect deadlock because some thread has been asleep for a long period of time?**

Recovery from deadlock

- **What should be done to recover?**
  - » **Abort deadlocked processes and reclaim resources**
  - » **Temporarily reclaim resource, if possible**
  - » **Abort one process at a time until deadlock cycle is eliminated**
- **Where to start?**
  - » **Low priority process**
  - » **How long process has been executing**
  - » **How many resources a process holds**
  - » **Batch or interactive**
  - » **Number of processes that must be terminated**

Other deadlock recovery techniques

- **Recovery through rollback**
  - » **Save state periodically**
    - – **take a checkpoint**
    - – **start computation again from checkpoint**
  - » **Done for large computation systems**

Review: Handling Deadlock

Ostrich algorithm

- Ignore
  - » Easiest and most common approach (e.g., UNIX).
- Deadlock prevention
  - » Ensure deadlock does not happen
  - » Ensure at least one of 4 conditions does not occur
- Deadlock detection and recovery
  - » Allow deadlocks, but detect when occur
  - » Recover and continue
- Deadlock avoidance
  - » Ensure deadlock does not happen
  - » Use information about resource requests to dynamically avoid unsafe situations

Deadlock avoidance

Don't allocate resource if it leads to deadlock

- Detection vs. avoidance…
  - » Detection – "optimistic" (pretends that everything is A-OK) approach
    - – Allocate resources
    - – "Break" system to fix it
  - » Avoidance – "pessimistic" (conservative) approach
    - – Don't allocate resources if it lead to deadlock
    - – If a process requests a resource...

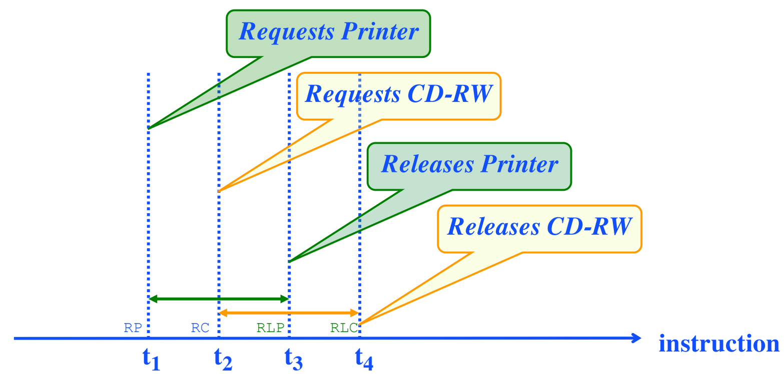
      ... make it wait until you are sure it's OK

      (see if it safe to proceed)
  - » Which one to use depends upon the application
- Lets create an Avoidance Deadlock Algorithm ! …

Process-resource trajectories

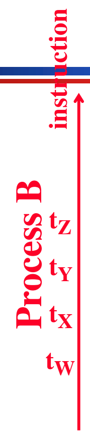
Process A

Process-resource trajectories



Process A

Process-resource trajectories



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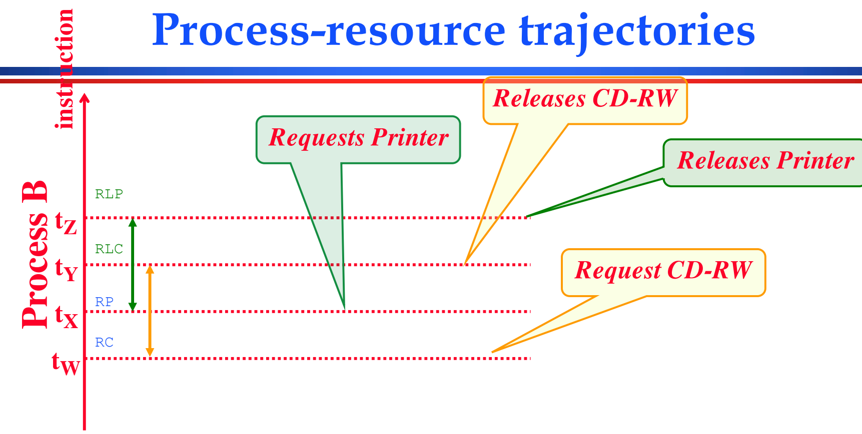

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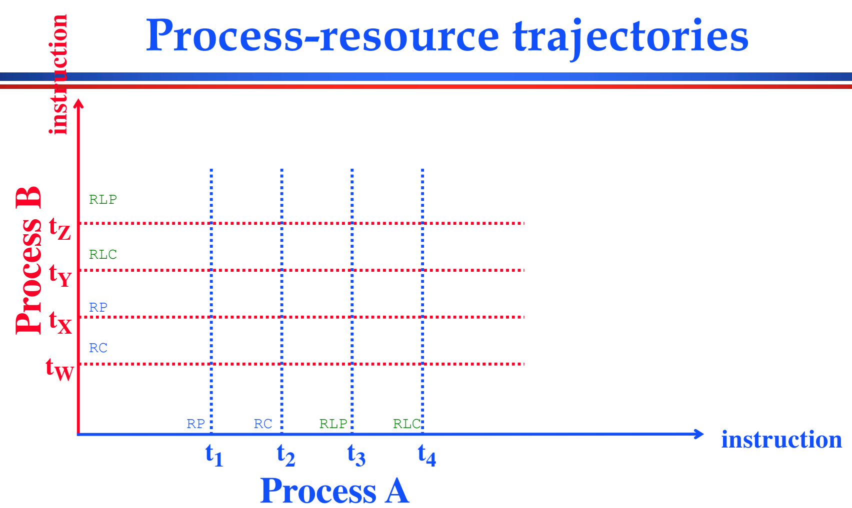

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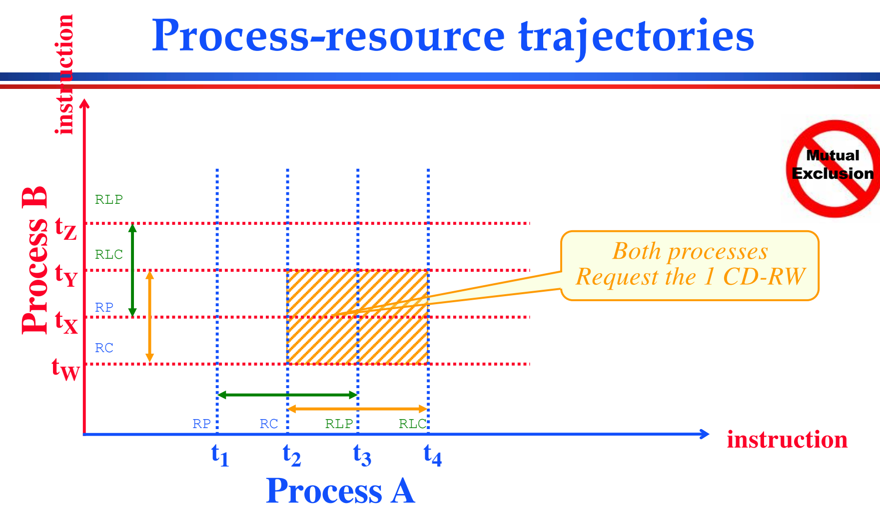

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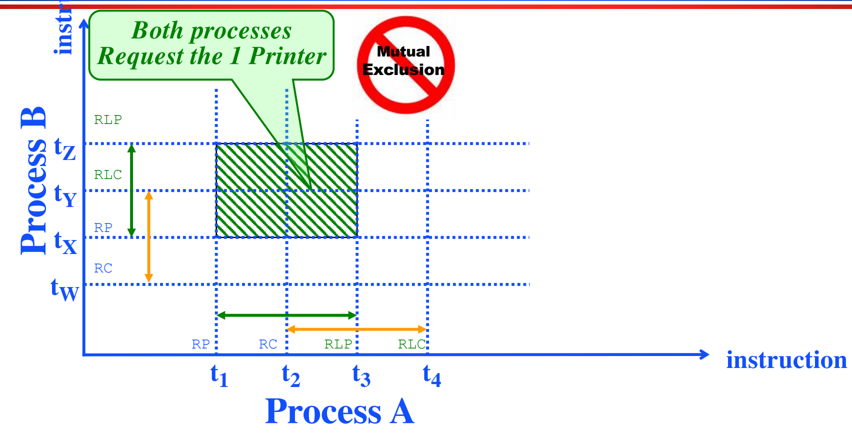

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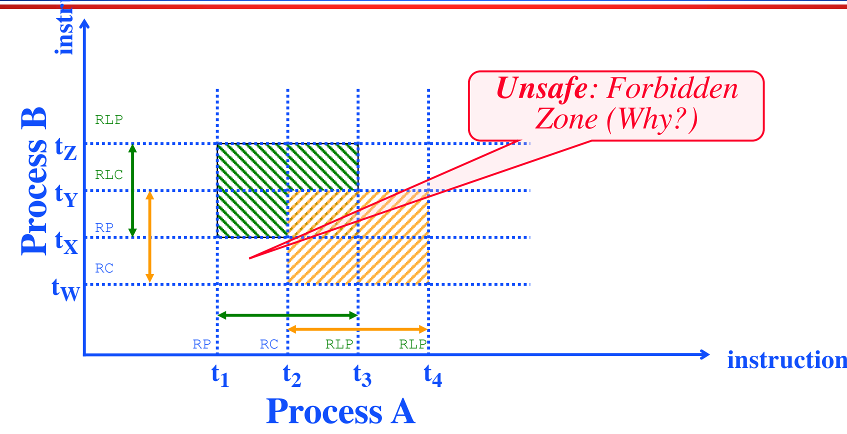

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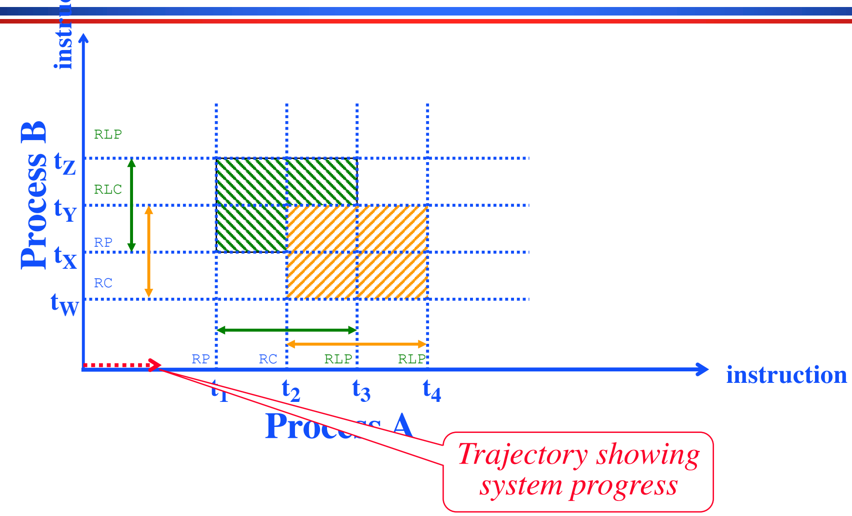

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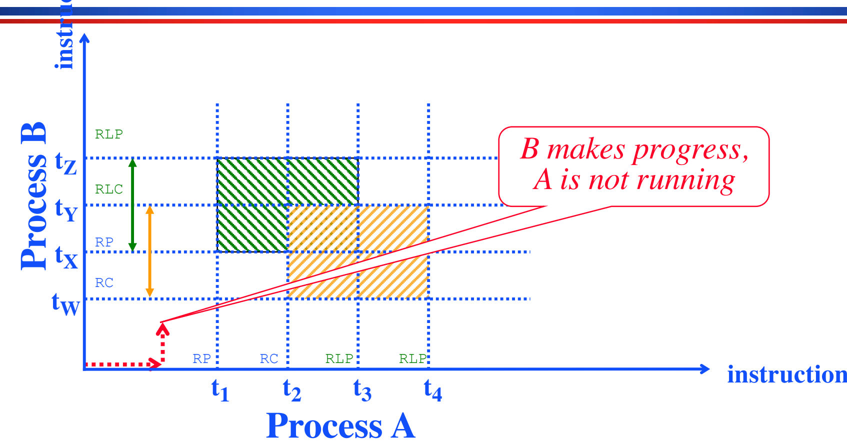

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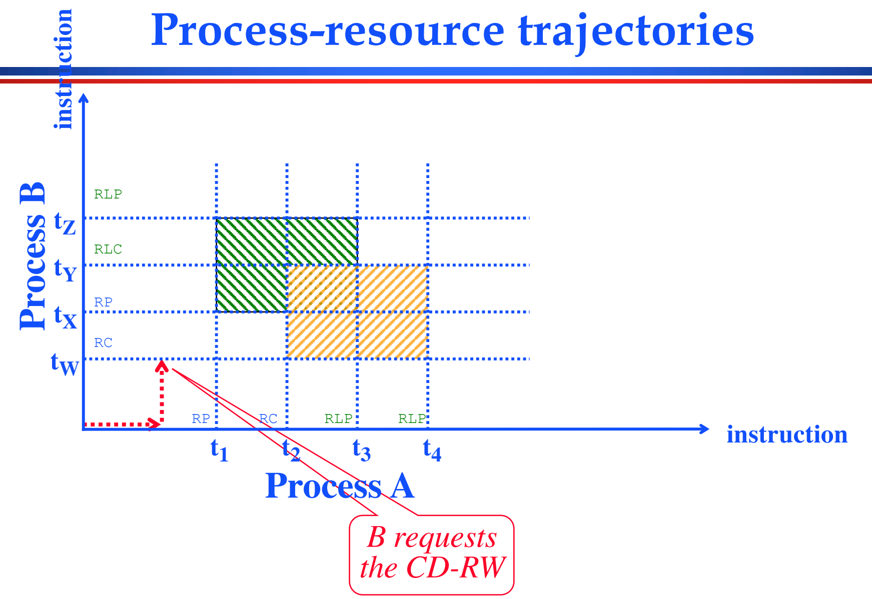

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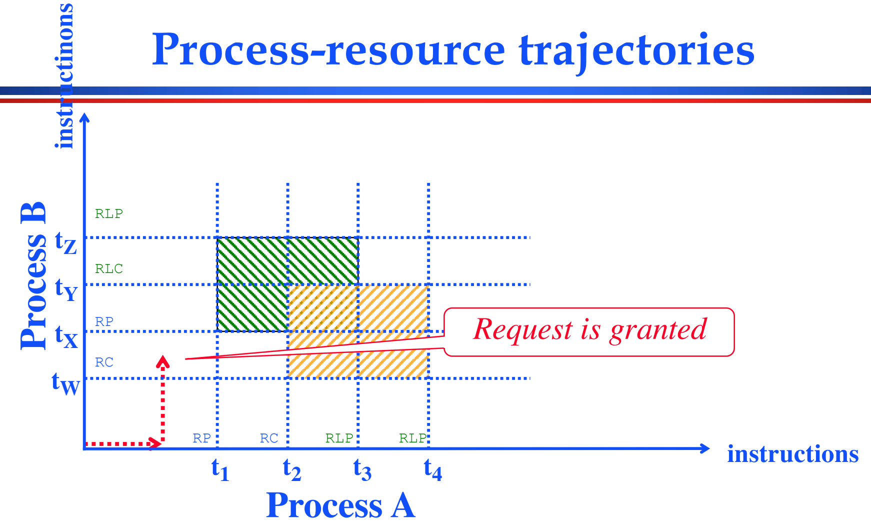

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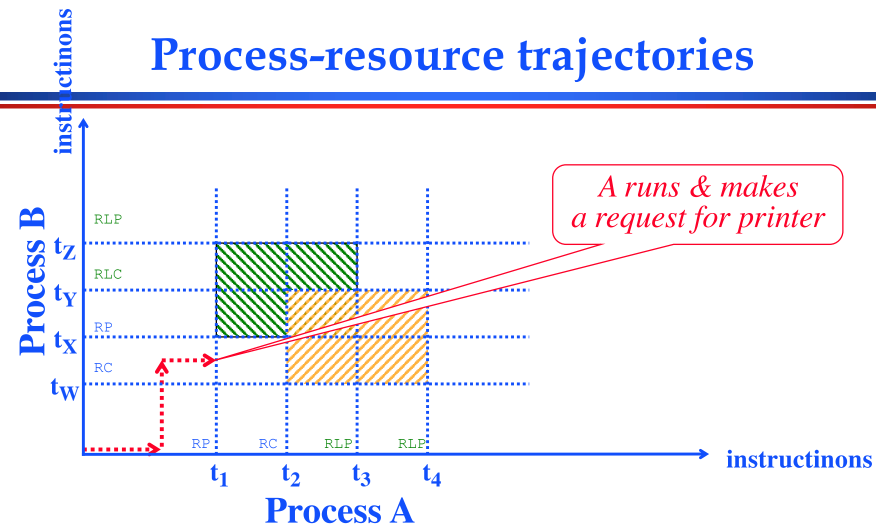

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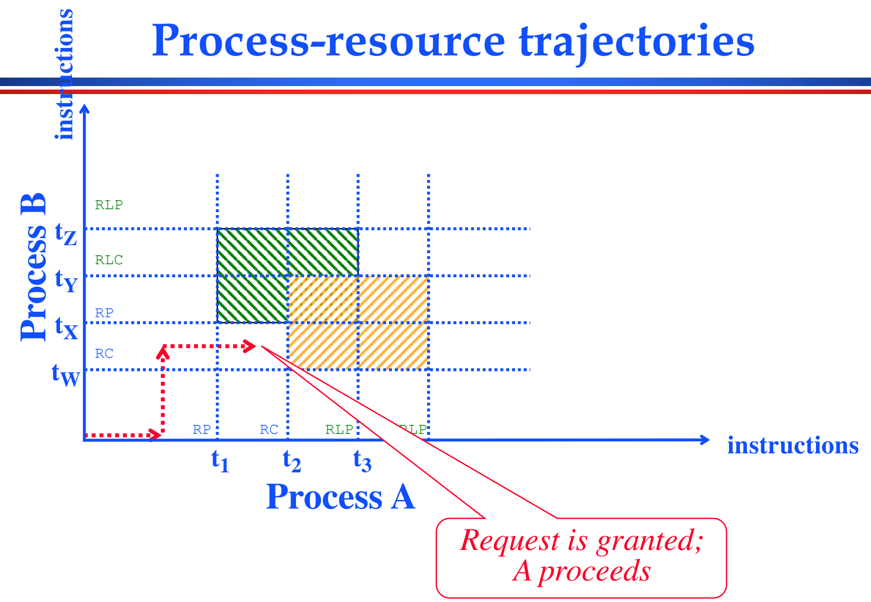

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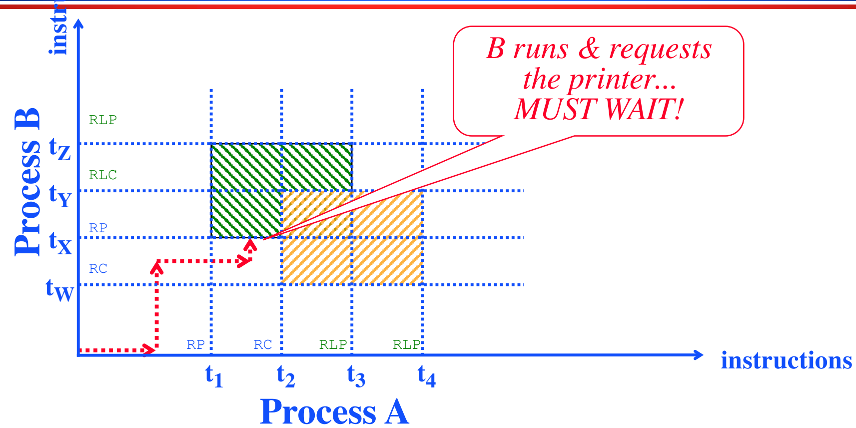

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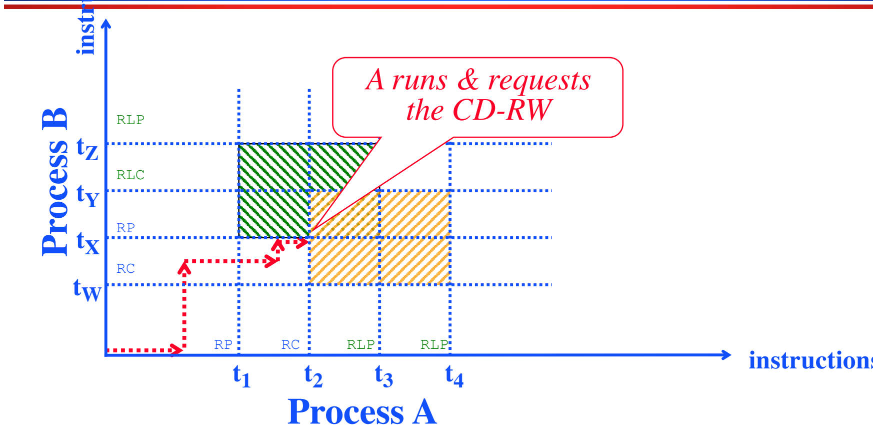
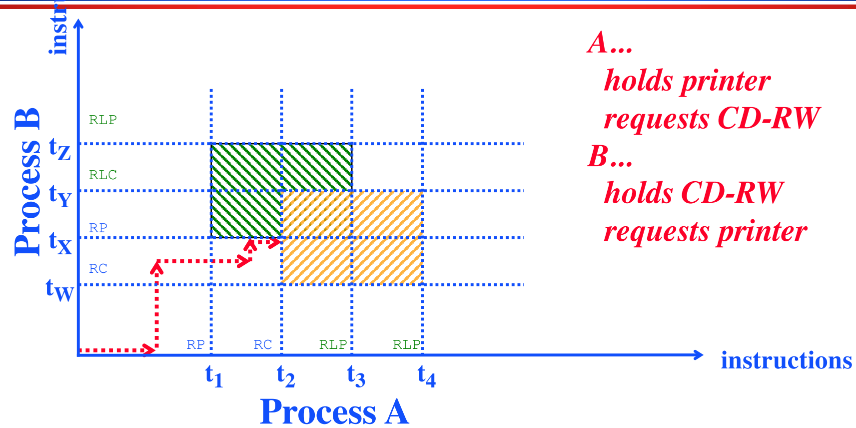


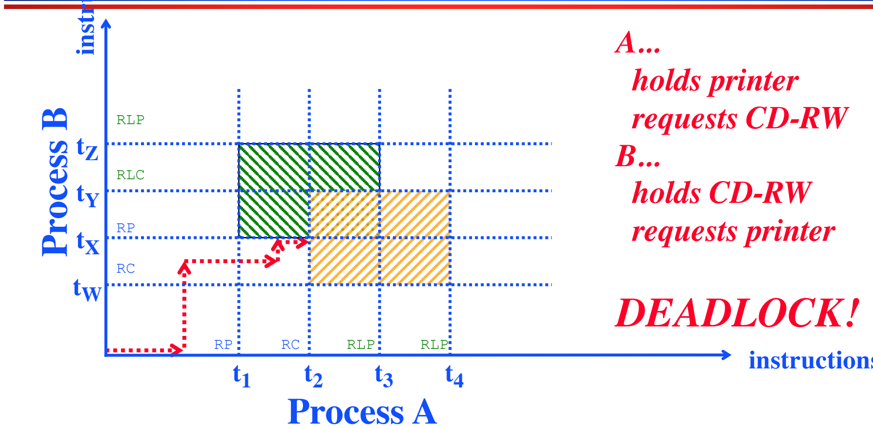
Process-resource trajectories



A...
- *holds printer*
- *requests CD-RW*

B...
- *holds CD-RW*
- *requests printer*

Process-resource trajectories

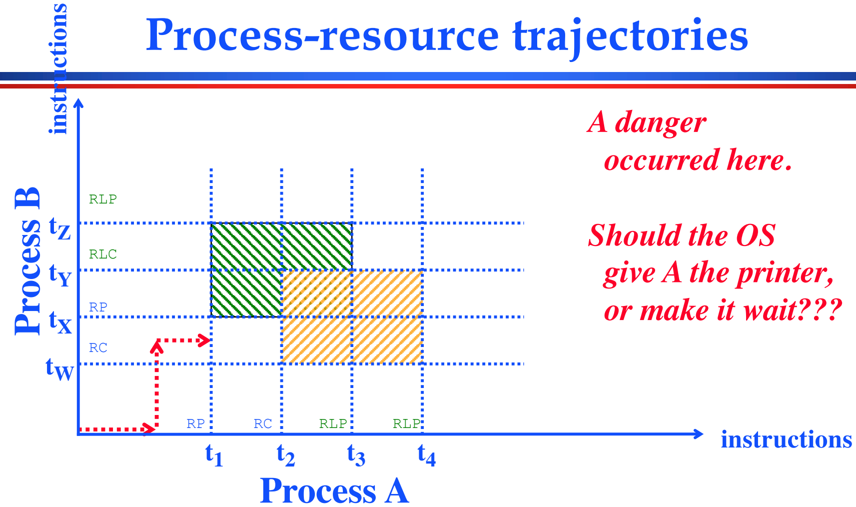


A...
- *holds printer*
- *requests CD-RW*

B...
- *holds CD-RW*
- *requests printer*

DEADLOCK!

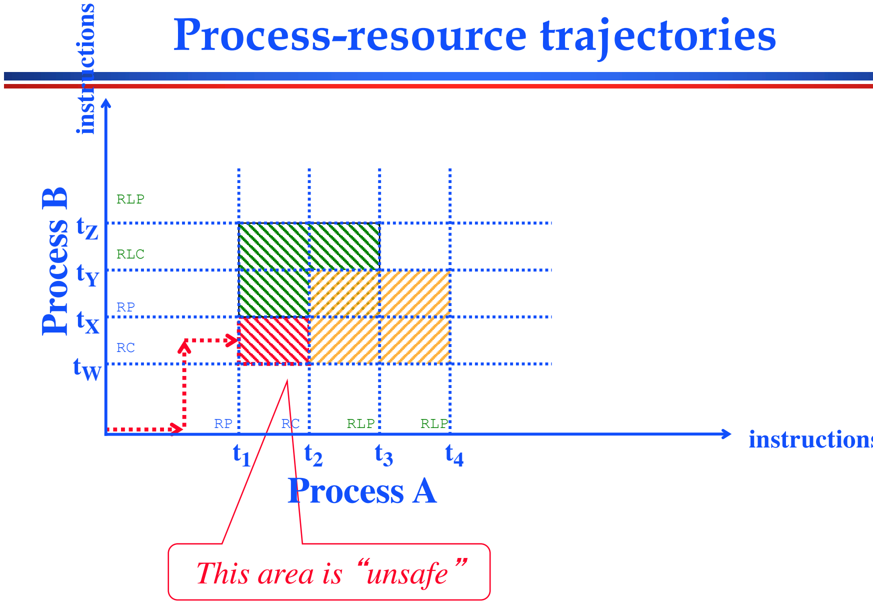
Process-resource trajectories



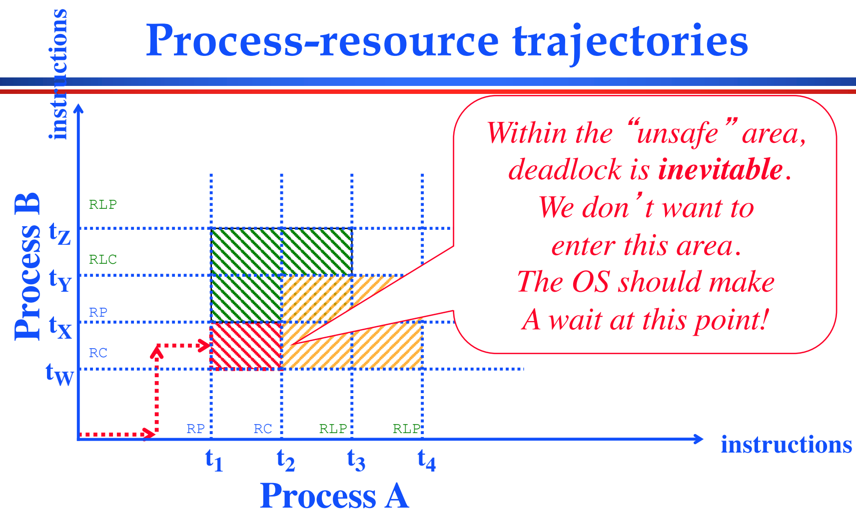
A danger occurred here.

Should the OS give A the printer, or make it wait???

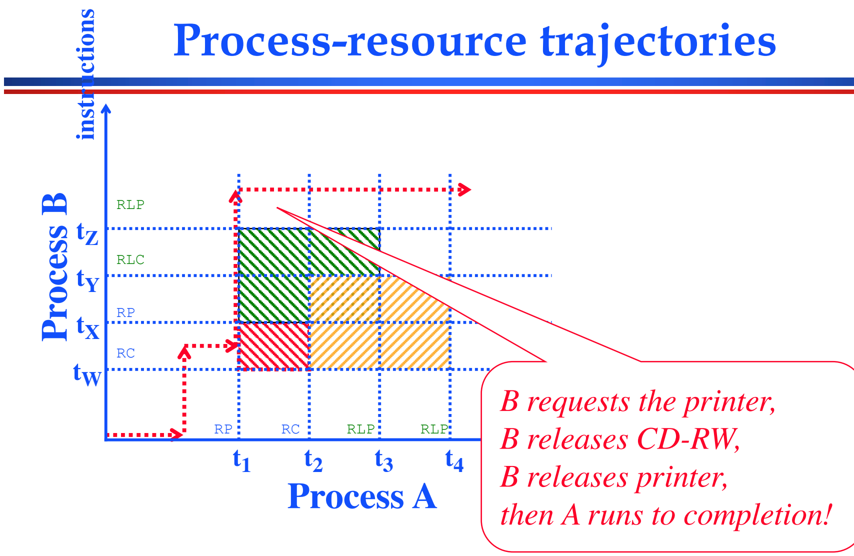
Process-resource trajectories



Process-resource trajectories



Process-resource trajectories



Safe states

- The current state:
  "which processes hold which resources"
- A "safe" state:
  - No deadlock, *and*
  - There is some scheduling order in which every process can run to completion even if all of them request their maximum number of units immediately
- The Banker's Algorithm:
  - *Goal*: Avoid unsafe states!!!
  - *Question: When a process requests more units, should the system (a) grant the request or (b) make it wait?*

Deadlock Avoidance

- Dijkstra's Banker's Algorithm
- Idea: Avoid unsafe states of processes holding resources
  - Unsafe states might lead to deadlock if processes make certain future requests
    - Eventually…
  - When process requests resource, only give if doesn't cause unsafe state
  - Problem: Requires processes to specify future resource demands.

The Banker's Algorithm

- **Assumptions:**
  - Only one type of resource, with multiple units.
  - Processes declare their maximum potential resource needs ahead of time (total sum is 22 units of credit but only has 10)
- *When a process requests more units should the system make it wait to ensure safety?*

Example: One resource type with 10 units

	Has	Max	
A	3	9	6
B	2	4	2
C	2	7	5

Free: 3

	Has	Max
A	3	9
B	4	4
C	2	7

Free: 1

	Has	Max
A	3	9
B	0	–
C	2	7

Free: 5

	Has	Max
A	3	9
B	0	–
C	7	7

Free: 0

	Has	Max
A	3	9
B	0	–
C	0	–

Free: 7

Safe states

- Safe state – "when system is not deadlocked and there is some scheduling order in which every process can run to completion even if all of them suddenly request their maximum number of resource immediately"

10 total

	Has	Max	
A	3	9	6
B	2	4	2
C	2	7	5

Free: 3 3

	Has	Max
A	3	9
B	4	4
C	2	7

Free: 1

	Has	Max
A	3	9
B	0	–
C	2	7

Free: 5

	Has	Max
A	3	9
B	0	–
C	7	7

Free: 0

	Has	Max
A	3	9
B	0	–
C	0	–

Free: 7

Unsafe/Safe state?

The difference here is A possesses 1 more resource

10 total

	Has	Max	
A	3	9	6
B	2	4	2
C	2	7	5

Free: 3

Safe

	Has	Max	
A	4	9	5
B	2	4	2
C	2	7	5

Free: 2

Unsafe!

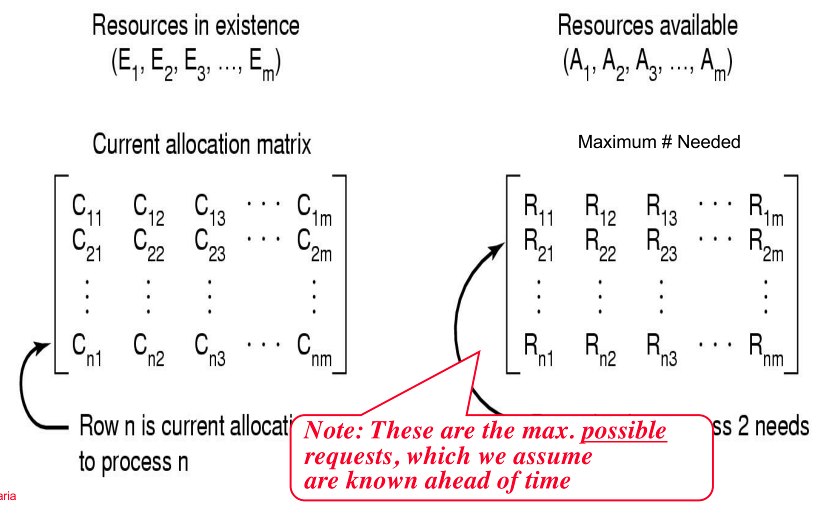
	Has	Max
A	4	9
B	4	4
C	2	7

Free: 0

	Has	Max
A	4	9
B	—	—
C	2	7

Free: 4

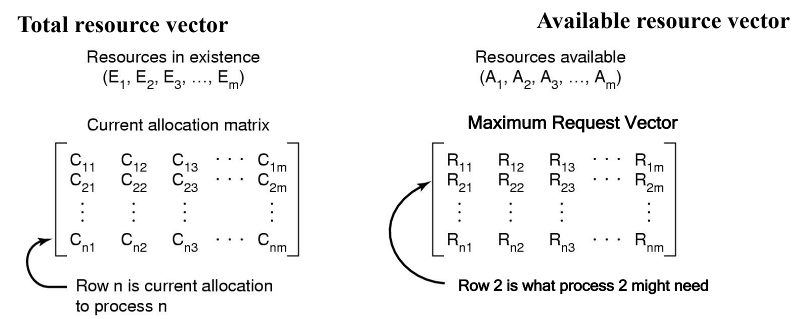
Avoidance with multiple resource types



Banker's algorithm for multiple resources

- Look for a row, *R*, whose unmet resource needs are all smaller than or equal to A. If no such row exists, the system will eventually deadlock since no process can run to completion
- Assume the process of the row chosen requests all the resources that it needs (which is guaranteed to be possible) and finishes. Mark that process as terminated and add all its resources to A vector
- Repeat steps 1 and 2, until either all process are marked terminated, in which case the initial state was safe, or until deadlock occurs, in which case it was not

Avoidance modeling



RUN ALGORITHM ON EVERY RESOURCE REQUEST

Avoidance algorithm

	Tape drives	Plotters	Scanners	CD Roms
E =	4	2	3	1

	Tape drives	Plotters	Scanners	CD Roms
A =	2	1	0	0

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

More needed matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

Avoidance algorithm

	Tape drives	Plotters	Scanners	CD Roms
E =	4	2	3	1

	Tape drives	Plotters	Scanners	CD Roms
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Avoidance algorithm

	Tape drives	Plotters	Scanners	CD Roms
E =	4	2	3	1

	Tape drives	Plotters	Scanners	CD Roms
A =	2	1	0	0
	2	**2**	**2**	**0**

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

More needed matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

Avoidance algorithm

	Tape drives	Plotters	Scanners	CD Roms
E =	4	2	3	1

	Tape drives	Plotters	Scanners	CD Roms
A =	2	1	0	0
	2	**2**	**2**	**0**

Current allocation matrix

C =

0	0	1	0
2	0	0	1
~~0~~	~~1~~	~~2~~	~~0~~

More needed matrix

R =

2	0	0	1
1	0	1	0
~~2~~	~~1~~	~~0~~	~~0~~

Avoidance algorithm

	Tape drives	Plotters	Scanners	CD Roms
E =	4	2	3	1

	Tape drives	Plotters	Scanners	CD Roms
A =	2	1	0	0
	2	**2**	**2**	**0**
	4	**2**	**2**	**1**

Current allocation matrix

C =

0	0	1	0
~~2~~	~~0~~	~~0~~	~~1~~
~~0~~	~~1~~	~~2~~	~~0~~

More needed matrix

R =

2	0	0	1
~~1~~	~~0~~	~~1~~	~~0~~
~~2~~	~~1~~	~~0~~	~~0~~

Deadlock avoidance

- **Deadlock avoidance is usually impossible**
  - » **because you don't know in advance what resources a process will need!**