

CS 370: OPERATING SYSTEMS

[DEADLOCKS]

Crux of safe sequences

Is there a sequence
Of process completions
Where each one's max needs are met
And their resources returned to the pool

If so
the system's in a safe state

Inspect each request
See if the request leads to a safe state
If so, let it through
If not, delay

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Frequently asked questions from the previous class survey

- ☐ If resources were hypothetically infinite, could deadlocks still occur?
- ☐ Conditions for starvation?
- ☐ Are particular deadlock prevention strategies better than others? Or is it dependent on the circumstances?
- ☐ Could there be a priority for resource preemption?
- ☐ Resource allocation graph: What if process needs to have a specific resource instance?
- ☐ In deadlock avoidance, are you always exploring all possible sequences?



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Topics covered in this lecture

- Deadlock Avoidance
 - ▣ Banker's Algorithm
- Deadlock Detection
 - ▣ And ... recovery
- Other issues relating to deadlocks



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A deadlock-prone system can be in one of three states: safe, unsafe, and deadlocked

- Safe state: For *any possible sequence of resource requests*, there is **at least one safe sequence** of processing the requests
 - ▣ That eventually succeeds in **granting** all pending and future requests
- Unsafe state: There is *at least one sequence* of future resource requests that **leads to deadlock**
- In a deadlocked state, the system has at least one deadlock



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A system in a safe state **controls its own destiny**

- For any workload, it can avoid deadlock by **delaying** the processing of some requests
 - ▣ Once the system enters an unsafe state, it may not be able to avoid deadlock
- In particular, the Banker's Algorithm (that we will look at next) **delays** any request that takes it from a safe to an unsafe state.



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BANKER'S ALGORITHM



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Banker's Algorithm

- Designed by Dijkstra
- Modeled on a small-town banker
 - ▣ Customers have been extended lines of credit
 - ▣ Not ALL customers will need their maximum credit immediately
- Customers make loan requests from time to time



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Crux of the Banker's Algorithm

- Consider each request as it occurs
 - ▣ See if granting it is safe
- If safe: grant it; If unsafe: postpone
- For safety: banker checks if there is **enough** to satisfy some customer
 - ▣ If so, that customer's loans are assumed to be repaid
 - ▣ Customer closest to limit is checked next
 - ▣ **If all loans can be repaid; state is safe: loan approved**



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Banker's Algorithm: Managing the customers. Banker has only reserved 10 units instead of 22

	Has	Max
A	0	6
B	0	5
C	0	4
D	0	7

Free: 10

SAFE

	Has	Max
A	1	6
B	1	5
C	2	4
D	4	7

Free: 2

Delay all requests except C

SAFE

	Has	Max
A	1	6
B	2	5
C	2	4
D	4	7

Free: 1

UNSAFE

*A customer may not need the entire credit line.
 But the banker cannot count on this behavior.*

There is **ONLY ONE** resource -- Credit



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Banker's algorithm: Crux

- Declare **maximum** number of resource instances needed
 - ▣ Cannot exceed resource thresholds
- Determine if resource allocations leave system in a safe state



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Bankers Algorithm: Data Structures [Overview]

	Allocation			Max			Available		
	A	B	C	A	B	C	A	B	C
P0	0	1	0	7	5	3	3	3	2
P1	2	0	0	3	2	2			
P2	3	0	2	9	0	2			
P3	2	1	1	2	2	2			
P4	0	0	2	4	3	3			

A, B, and C are different types of resources



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Data Structures: **n** is the number of processes and **m** is the number of resource types

- Available: Vector of length m
 - ▣ Number of resources for each type
 - $\text{Available}[i] = k$
- Max: $n \times m$ matrix
 - ▣ Maximum *demand* for each process (in each row)
 - ▣ $\text{Max}[i, j] = k$
 - Process P_i may request at most k instances of R_j



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Data Structures: n is the number of processes and m is the number of resource types

- Allocation: $n \times m$ matrix
 - ▣ Resource instances allocated for each process (each row)
 - ▣ Allocation[i, j]=k
 - Process P_i currently **allocated** k instances of R_j
- Need: $n \times m$ matrix
 - ▣ Resource instances needed for each process (each row)
 - ▣ Need[i, j]=k
 - Process P_i **may need** k **more** instances of R_j



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Vectors identifying a process' resource requirements:
Rows in the matrices

- Allocation_i
 - ▣ Resource instances allocated for process P_i
- Need_i
 - ▣ Additional resource instances that process P_i may still request



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Banker's Algorithm: Notations

- \mathbf{X} and \mathbf{Y} are vectors of length m
- $\mathbf{X} \leq \mathbf{Y}$ if-and-only-if
 $\mathbf{X}[i] \leq \mathbf{Y}[i]$ *for all* $i=1, 2, \dots, m$
- $\mathbf{X} = \{1, 7, 3, 2\}$ and $\mathbf{Y} = \{0, 3, 2, 1\}$
So, $\mathbf{Y} \leq \mathbf{X}$
Also, $\mathbf{Y} < \mathbf{X}$ if $\mathbf{Y} \leq \mathbf{X}$ and $\mathbf{Y} \neq \mathbf{X}$



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Banker's Algorithm: Resource-request

- Request _{i} : Request vector for process P_i
 - ▣ Request _{i} [j]= k
 - Process P_i wants k instances of R_j



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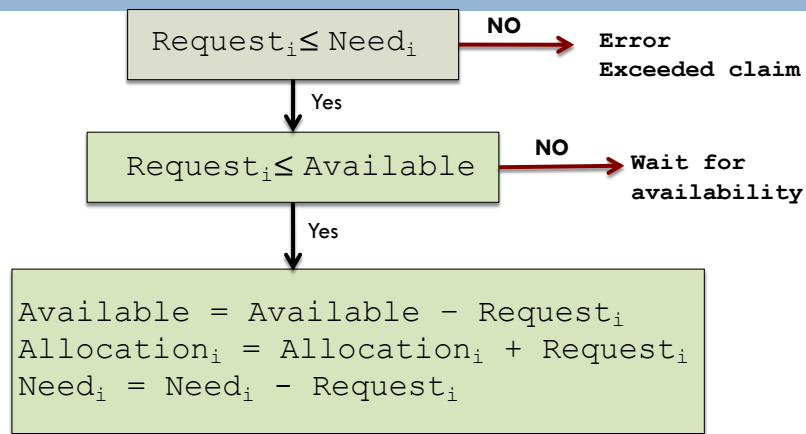
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Banker's Algorithm: Resource-request



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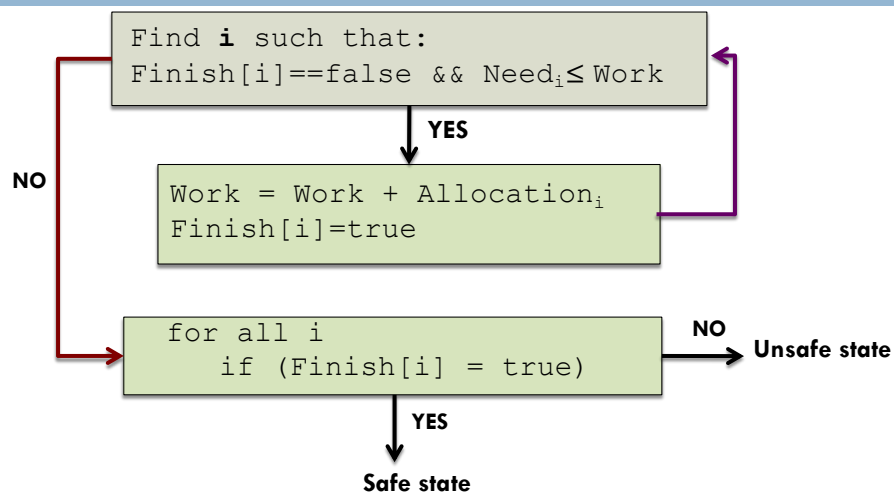
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Bankers Algorithm: Safety

Initialize $\text{Work} = \text{Available}$



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Bankers Algorithm: Example

	Allocation			Max			Available		
	A	B	C	A	B	C	A	B	C
P0	0	1	0	7	5	3	3	3	2
P1	2	0	0	3	2	2			
P2	3	0	2	9	0	2			
P3	2	1	1	2	2	2			
P4	0	0	2	4	3	3			

$\langle P1, P3, P4, P2, P0 \rangle$ satisfies safety criteria

Suppose process P1 requests 1 A, and 2 Cs: $Request_1 = (1,0,2)$

$Request_1 \leq Available$

Pretend request was fulfilled



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Bankers Algorithm: Example

	Allocation			Max			Available		
	A	B	C	A	B	C	A	B	C
P0	0	1	0	7	5	3	2	3	0
P1	3	0	2	3	2	2			
P2	3	0	2	9	0	2			
P3	2	1	1	2	2	2			
P4	0	0	2	4	3	3			

$\langle P1, P3, P4, P0, P2 \rangle$ satisfies safety criteria

$Request_4 = (3,3,0)$ from process P4 cannot be granted: resources unavailable

$Request_0 = (0,2,0)$ from process P0 cannot be granted: unsafe state



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Bankers Algorithm: Example

	Allocation			Max			Available		
	A	B	C	A	B	C	A	B	C
P0	0	3	0	7	5	3	2	1	0
P1	3	0	2	3	2	2			
P2	3	0	2	9	0	2			
P3	2	1	1	2	2	2			
P4	0	0	2	4	3	3			

None of the processes can now satisfy their max resource needs.

Request₀ = (0,2,0) from process P0 cannot be granted: unsafe state



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Bankers Algorithm: Practical implications [1/2]

- Understanding the Banker's Algorithm can help in designing simple solutions for specific problems
- Banker's Algorithm to devise a rule for thread safe acquisition of a pair of locks, **A** and **B**, with **mutually recursive** locking?
 - ▣ Suppose a thread needs to acquire locks **A** and **B**, in that order, while another thread needs to acquire lock **B** first, then **A**
 - ▣ RULE: A thread is always allowed to acquire its second lock
 - Acquire first lock provided the other thread does not already hold its first lock



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Bankers Algorithm: Practical implications [2/2]

- Processes *rarely know in advance* about their maximum resource needs
- Number of processes managed by the kernel is not fixed
 - ▣ Varies dynamically
- Resources thought to be available can vanish



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DEADLOCK DETECTION

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Single instance of EACH resource type

- Use **wait-for** graph
 - ▣ *Variant* of the resource allocation graph
- Deadlock exists if there is a **cycle** in the graph
- Transformation
 - ① **Remove** resource nodes
 - ② **Collapse** appropriate edges



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What the edges in the wait-for graph imply

- $P_i \rightarrow P_j$
 - ▣ Process P_i is waiting for a resource held by P_j
- $P_i \rightarrow P_j$ only if resource allocation graph has
 - ① $P_i \rightarrow R_q$ and
 - ② $R_q \rightarrow P_j$ for some resource R_q



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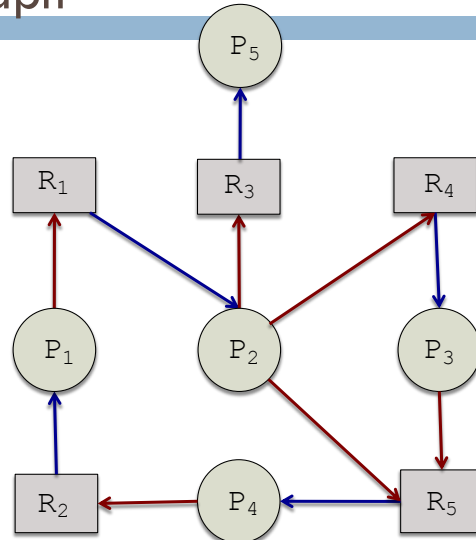
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Transforming a resource allocation graph into a wait-for graph



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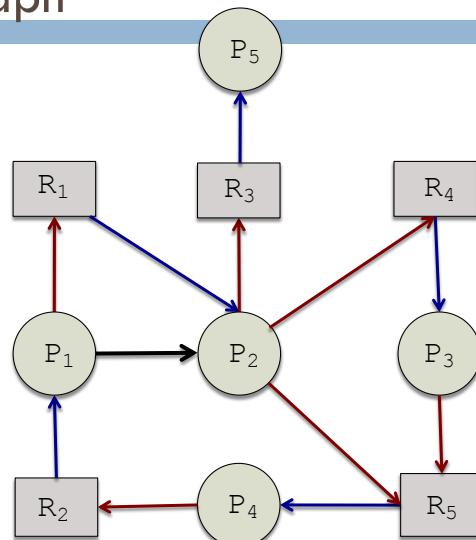
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Transforming a resource allocation graph into a wait-for graph



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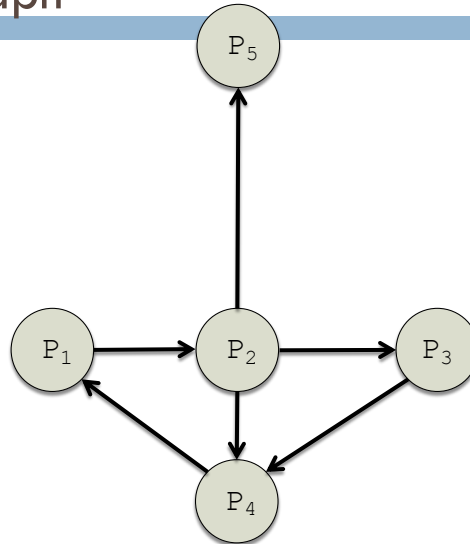
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Transforming a resource allocation graph into a wait-for graph



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Deadlock detection for multiple instances of a resource type

- Wait-for graph is not applicable
- Approach uses data structures similar to Banker's algorithm



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Data Structures: n is number of processes m is number of resource types

- Available: Vector of length m
 - ▣ Number of resources for each type
- Allocation: $n \times m$ matrix
 - ▣ Resource instances allocated for each process
 - ▣ $\text{Allocation}[i, j] = k$
 - Process P_i currently **allocated** k instances of R_j
- Request: $n \times m$ matrix
 - ▣ Current request for each process
 - ▣ $\text{Request}[i, j] = k$
 - Process P_i **requests** k **more** instances of R_j



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Deadlock detection: Initialization

Work and Finish are vectors of length m & n

```
Work = Available
if (Allocationi ≠ 0) {
    Finish[i] = false;
} else {
    Finish[i] = true;
}
```



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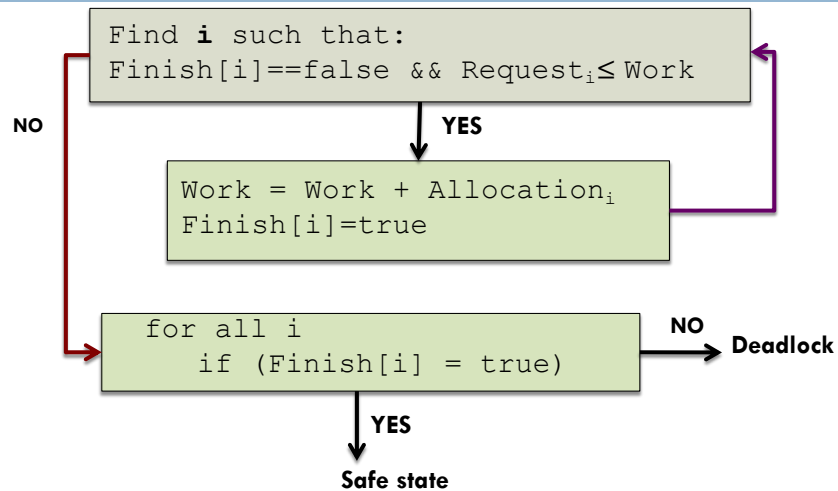
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Deadlock detection



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Deadlock detection: Usage

- How **often** will the deadlock occur?
- How **many** processes will be affected when it happens?



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Frequency of invoking deadlock detection

- Resources allocated to deadlocked process **idle**
 - ▣ Until the deadlock can be broken
- Deadlocks occur **only** when process makes a request
 - ▣ Significant overheads to run detection per request
- Middle ground: Run at **regular intervals**



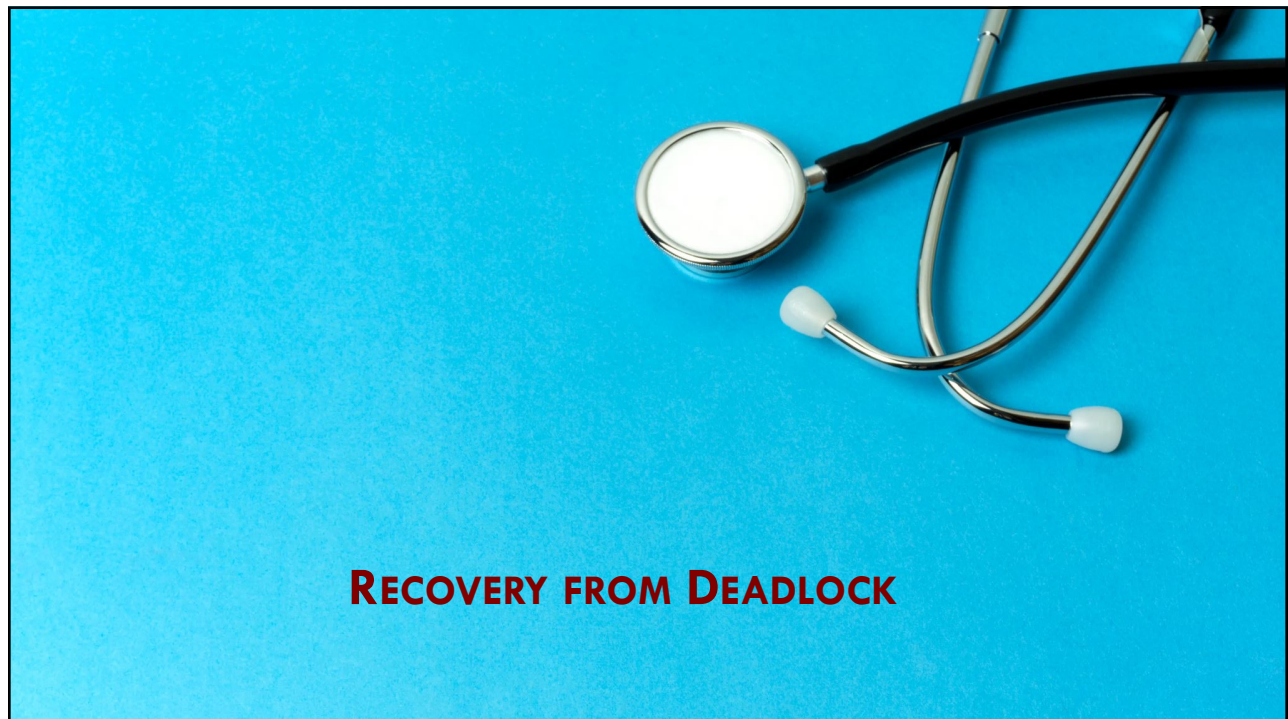
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Recovery from deadlock

- Automated or manual
- OPTIONS
 - ▣ Break the circular wait: **Terminate processes**
 - ▣ **Preempt** resources from deadlocked process(es)



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Breaking circular wait: Process termination

- Terminate **all** deadlocked processes
- Terminate processes **one at a time**
 - ▣ After each termination, check if deadlock *persists*
- Reclaim all resources allocated to terminated process



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Terminating a Process

- Process may be in the midst of something
 - ▣ Updating files, printing data, etc.
- Terminate process whose termination will incur **minimum** costs
 - ▣ Policy decision similar to scheduling decisions



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Factors determining process termination

- Priority
- How long has the process been running?
 - ▣ How much longer?
- Number and types of resources used
 - ▣ How many more needed?
- Interactive or batch



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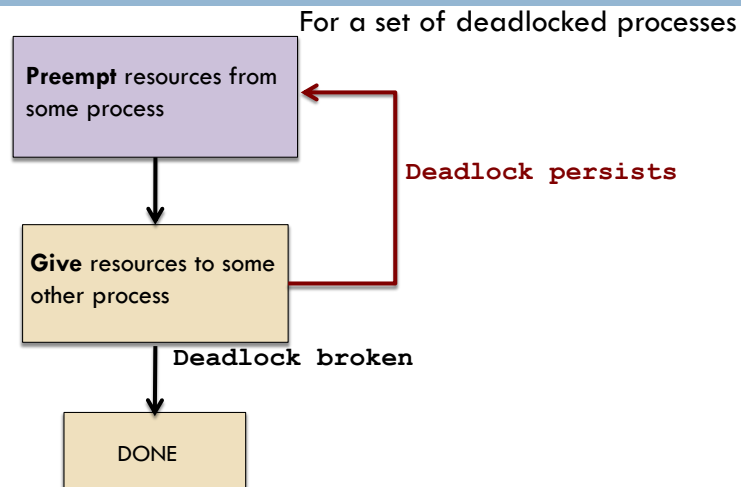
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Deadlock recovery: Resource preemption



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Resource preemption: Issues

- Selecting a victim
 - ▣ Which resource and process
 - ▣ Order of preemption to minimize cost
- Starvation
 - ▣ Process can be selected for preemption *finite* number of times



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Deadlock recovery through rollbacks

- **Checkpoint** process periodically
 - ▣ Contains memory image and resource state
- Deadlock detection tells us *which* resources are needed
- Process owning a needed resource
 - ▣ **Rolled back** to before it acquired needed resource
 - Work done since rolled back checkpoint discarded
 - ▣ **Assign** resource to deadlocked process



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OTHER ISSUES

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Two-phase locking

- Used in database systems
- Operation involves requesting locks on several records and updating all the locked records
- When multiple processes are running?
 - ▣ Possibility of deadlocks



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Two-Phase Locking

- First phase
 - ▣ Process tries to acquire all the locks it needs, one at time
 - ▣ If successful: start second-phase
 - ▣ If some record is already locked?
 - Release all locks and start the first phase all over
- Second-phase
 - ▣ Perform updates and release the locks



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Communication Deadlocks

- Process **A** sends a request message to process **B**
 - ▣ Blocks until **B** sends a reply back
- Suppose, that the request was lost
 - ▣ **A** is blocked waiting for a reply
 - ▣ **B** is blocked waiting for a request to do something
 - ▣ **Communication deadlock**



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Communication deadlocks

- Cannot be prevented by ordering resources (there are none)
 - ▣ Or avoided by careful scheduling (no moments when a request can be postponed)
- Solution to breaking communication deadlocks?
 - ▣ **Timeouts**
 - Start a timer when you send a message to which a reply is expected.



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Livelocks

- Polling (busy waits) used to enter critical section or access a resource
 - ▣ Typically used for a short time when overhead for suspension is considered greater
- In a livelock two processes need each other's resource
 - ▣ Both run and make no progress, but neither process blocks
 - ▣ **Use CPU quantum over and over without making progress**



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Livelocks do occur

- If fork fails because process table is full
 - ▣ Wait for some time and try again
- But there could be a collection of processes each trying to do the same thing



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The contents of this slide-set are based on the following references

- *Avi Silberschatz, Peter Galvin, Greg Gagne. Operating Systems Concepts, 9th edition. John Wiley & Sons, Inc. ISBN-13: 978-1118063330. [Chapter 7]*
- *Andrew S Tanenbaum and Herbert Bos. Modern Operating Systems. 4th Edition, 2014. Prentice Hall. ISBN: 013359162X/ 978-0133591620. [Chapter 6]*
- *Thomas Anderson and Michael Dahlin. Operating Systems Principles and Practice. 2nd Edition. ISBN: 978-0985673529. [Chapter 6]*



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