

Resource-Allocation Graph (Review)

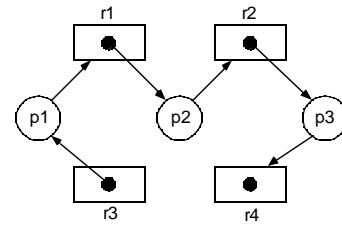
- The deadlock conditions can be modeled using a directed graph called a *resource-allocation graph* (RAG)
 - 2 kinds of nodes:
 - *Boxes* — represent resources
 - Instances of the resource are represented as dots within the box
 - *Circles* — represent threads / processes
 - 2 kinds of (directed) edges:
 - *Request edge* — from process to resource — indicates the process has requested the resource, and is waiting to acquire it
 - *Assignment edge* — from resource instance to process — indicates the process is holding the resource instance
 - When a request is made, a request edge is added
 - When request is fulfilled, the request edge is transformed into an assignment edge
 - When process releases the resource, the assignment edge is deleted

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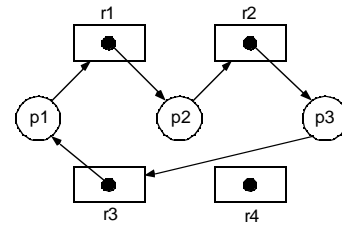
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Interpreting a RAG With Single Resource Instances (Review)

- If the graph does **not** contain a cycle, then **no** deadlock exists



- If the graph **does** contain a cycle, then a deadlock **does** exist



- With single resource instances, a cycle is a necessary and sufficient condition for deadlock

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Deadlock Detection (Single Resource of Each Type)

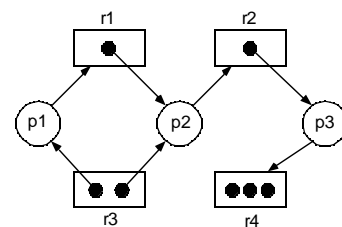
- If all resources have only a single instance, deadlock can be detected by searching the resource-allocation graph for cycles
 - Silberschatz defines a simpler graph, called the *wait-for* graph, and searches that graph instead
 - The wait-for graph is the resource-allocation graph, minus the resources
 - An edge from p1 to p2 means p1 is waiting for a resource that p2 holds (here we don't care which resource is involved)
- One simple algorithm:
 - Start at each node, and do a depth-first search from there
 - If a search ever comes back to a node it's already found, then it has found a cycle

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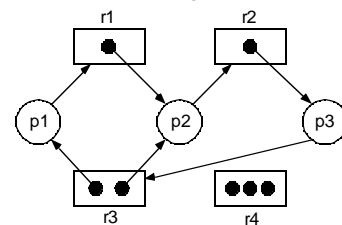
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Interpreting a RAG With Multiple Resource Instances

- If the graph does **not** contain a cycle, then **no** deadlock exists



- If the graph **does** contain a cycle, then a deadlock **may** exist



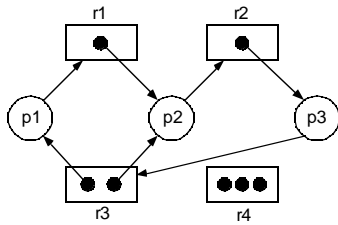
- With multiple resource instances, a cycle is a necessary (but not sufficient) condition for deadlock

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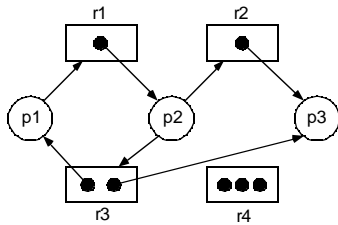
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Interpreting a RAG With Multiple Resource Instances (cont.)

- If the graph **does** contain a knot (and a cycle), then a deadlock **does** exist



- If the graph **does not** contain a knot, then a deadlock **does not** exist



- With multiple resource instances, a knot is a sufficient condition for deadlock

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Deadlock Detection (Multiple Resources of Each Type)

- This algorithm (Coffman, 1971) uses the following data structures:

Existing Resources
(E1, E2, E3, ..., Em)

Available Resources
(A1, A2, A3, ..., Am)

Current Allocation					Request				
C11	C12	C13	...	C1m	R11	R12	R13	...	R1m
C21	C22	C23	...	C2m	R21	R22	R23	...	R2m
.
.
Cn1	Cn2	Cn3	...	Cnm	Rn1	Rn2	Rn3	...	Rnm

- n processes, m types of resources

- **Existing Resources** vector tells number of resources of each type that exist
- **Available Resources** vector tells number of resources of each type that are available (unassigned to any process)
- i-th row of **Current Allocation** matrix tells number of resources of each type allocated (assigned) to process i

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Deadlock Detection (Multiple Resources of Each Type) (cont.)

- Every resource is either allocated or available
 - Number of resources of type j that have been allocated to all processes, plus number of resources of type j that are available, should equal number of resources of type j in existence
- Processes may have unfulfilled requests
 - i-th row of **Request** matrix tells number of resources of each type process i has requested, but not yet received
- Notation: comparing vectors
 - If A and B are vectors, the relation $A \leq B$ means that each element of A is less than or equal to the corresponding element of B (i.e., $A \leq B$ iff $A_i \leq B_i$ for $0 \leq i \leq m$)
 - Furthermore, $A < B$ iff $A \leq B$ and $A \neq B$

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Deadlock Detection Algorithm (Multiple Resources of Each Type)

- Operation:
 - Every process is initially unmarked
 - As algorithm progresses, processes will be marked, which indicates they are able to complete, and thus are not deadlocked
 - When algorithm terminates, any unmarked processes are deadlocked
- Algorithm:
 1. Look for an unmarked process P_i for which the i-th row of the **Request** matrix is less than or equal to the **Available** vector
 2. If such a process is found, add the i-th row of the **Current** matrix to the **Available** vector, mark the process, and go back to step 1
 3. If no such process exists, the algorithm terminates

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Deadlock Detection Example (Multiple Resources of Each Type)

Existing Resources
(4 2 3 1)

Available Resources
(2 1 0 0)

Current Allocation

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

Request

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

resources = (tape drive plotter printer CDROM)

■ Whose request can be fulfilled?

- Process 1 — no — no CDROM available
- Process 2 — no — no printer available
- Process 3 — yes — give it the requested resources, and after it completes and releases those resources, $A = (2 \ 2 \ 2 \ 0)$
- Process 1 still can't run (no CDROM), but process 2 can run, giving $A = (4 \ 2 \ 2 \ 1)$
- Process 1 can run, giving $A = (4 \ 2 \ 3 \ 1)$

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After Deadlock Detection: Deadlock Recovery

- How often does deadlock detection run?
 - After every resource request?
 - Less often (e.g., every hour or so, or whenever resource utilization gets low)?
- What if OS detects a deadlock?
 - Terminate a process
 - All deadlocked processes
 - One process at a time until no deadlock
 - Which one?
 - One with most resources?
 - One with less cost?
 - » CPU time used, needed in future
 - » Resources used, needed
 - That's a choice similar to CPU scheduling
 - Is it acceptable to terminate process(es)?
 - May have performed a long computation
 - » Not ideal, but OK to terminate it
 - Maybe have updated a file or done I/O
 - » Can't just start it over again!

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After Deadlock Detection: Deadlock Recovery (cont.)

■ Any less drastic alternatives?

- Preempt resources
 - One at a time until no deadlock
 - Which "victim"?
 - Again, based on cost, similar to CPU scheduling
 - Is rollback possible?
 - *Preempt* resources — take them away
 - *Rollback* — "roll" the process back to some safe state, and restart it from there
 - » OS must *checkpoint* the process frequently — write its state to a file
 - Could roll back to beginning, or just enough to break the deadlock
 - » This second time through, it has to wait for the resource
 - » Has to keep multiple checkpoint files, which adds a lot of overhead
 - Avoid starvation
 - May happen if decision is based on same cost factors each time
 - Don't keep preempting same process (i.e., set some limit)

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