Deadlock Conditions

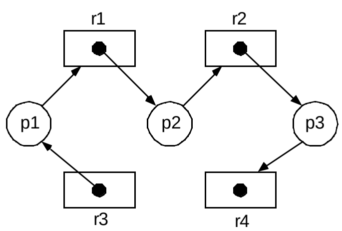
- These 4 conditions are **necessary** and **sufficient** for deadlock to occur:
  - **Mutual exclusion** — if one process holds a resource, other processes requesting that resource must wait until the process releases it (only one can use it at a time)
  - **Hold and wait** — processes are allowed to *hold* one (or more) resource and be *waiting* to acquire additional resources that are being held by other processes
  - **No preemption** — resources are released voluntarily; neither another process nor the OS can force a process to release a resource
  - **Circular wait** — there must exist a set of waiting processes such that P0 is waiting for a resource held by P1, P1 is waiting for a resource held by P2, … Pn-1 is waiting for a resource held by Pn, and Pn is waiting for a resource held P0

Resource-Allocation Graph

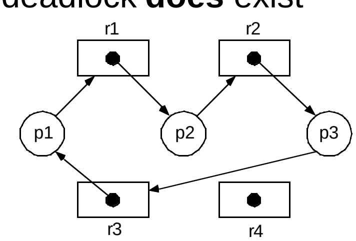
- The deadlock conditions can be modeled using a directed graph called a *resource-allocation graph* (RAG)
  - 2 kinds of nodes:
    - *Boxes* — represent resources
      - Instances of the resource are represented as dots within the box
    - *Circles* — represent threads / processes
  - 2 kinds of (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

Interpreting a RAG With Single Resource Instances

- If the graph does **not** contain a <u>cycle</u>, then **no** deadlock exists



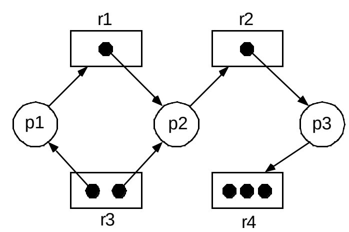
- If the graph **does** contain a <u>cycle</u>, then a deadlock **does** exist



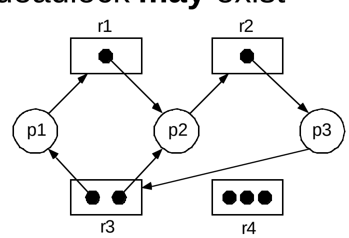
- With <u>**single**</u> resource instances, a <u>**cycle**</u> is a <u>**necessary**</u> and <u>**sufficient**</u> condition for deadlock

Interpreting a RAG With Multiple Resource Instances

- If the graph does **not** contain a <u>cycle</u>, then **no** deadlock exists



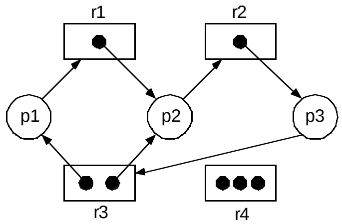
- If the graph **does** contain a <u>cycle</u>, then a deadlock **may** exist



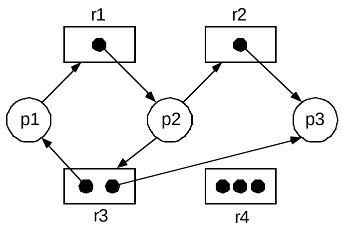
- With <u>**multiple**</u> resource instances, a <u>**cycle**</u> is a <u>**necessary**</u> (but not <u>**sufficient**</u>) condition for deadlock

Interpreting a RAG With Multiple Resource Instances (cont.)

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



- If the graph **does not** contain a <u>knot</u>, then a deadlock **does not** exist



- With <u>**multiple**</u> resource instances, a <u>**knot**</u> is a <u>**sufficient**</u> condition for deadlock

Dealing with Deadlock

- *The Ostrich Approach* — stick your head in the sand and ignore the problem
  - Often used in centralized systems!
  - Maybe also be a good solution for distributed systems in many situations
- *Deadlock avoidance* — consider each resource request, and only fulfill those that will not lead to deadlock
  - Stay in a *safe state* — a state with no deadlock where resource requests can be granted in some order such that all processes will complete
  - ✘ A bad solution for centralized systems, even worse in distributed systems
    - Must know resource requirements of all processes in advance
    - Resource request set is known and fixed, resources are known and fixed
    - Complex analysis for every request

Dealing with Deadlock (cont.)

- *Deadlock prevention* — eliminate one of the 4 deadlock conditions
  - Occasionally used in centralized systems!
  - Maybe also be a good solution for distributed systems in some situations
  - We'll come back to this later
- *Deadlock detection* and *recovery* — detect, then break the deadlock
  - Not too hard for single resource instances, harder for multiple resource instances
  - ✘ More difficult when state is distributed
  - ✔ Can detect concurrently w/ other activities

➡ In distributed systems — assume only one non-sharable resource of each type

Deadlock Detection in a Distributed Environment

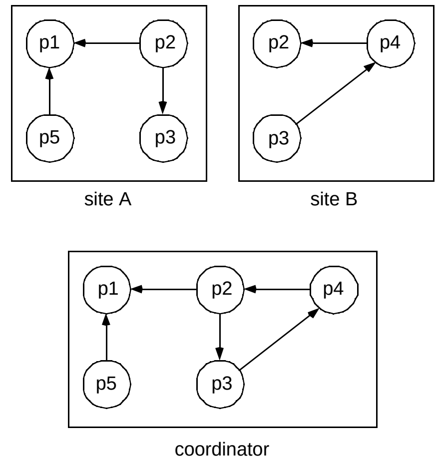
- Centralized algorithms
  - Coordinator maintains global WFG and searches it for cycles
  - Ho and Ramamoorthy's two-phase and one-phase algorithms
- Distributed algorithms
  - Global WFG, with responsibility for detection spread over many sites
  - Obermarck's path-pushing
  - Chandy, Misra, and Haas's edge-chasing
- Hierarchical algorithms
  - Hierarchical organization, site detects deadlocks involving only its descendants
  - Menasce and Muntz's algorithm
  - Ho and Ramamoorthy's algorithm

Centralized Deadlock Detection (Simple Algorithms)

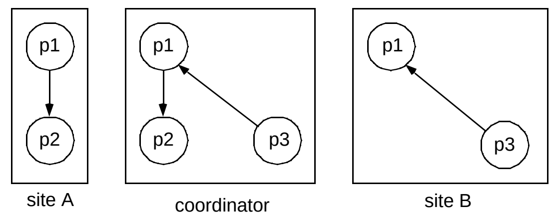
- First Algorithm
  - A central coordinator maintains a global wait-for graph (WFG) for the system
    - When appropriate, it checks the WFG for cycles (for single resource instances, a cycle implies deadlock)
    - WFG is resource-allocation graph minus resources; shows that a thread is waiting for a resource held by another thread
  - All sites request and release resources (even local resources) by sending *request* and *release* messages to the coordinator
    - When coordinator receives a *request*, it
      - updates the global WFG
      - checks for deadlocks
      - grants the request if no deadlock results
    - When coordinator receives a *release*, it
      - updates the global WFG
  - ✘ Large communication overhead, coordinator is a performance bottleneck and single point of failure, etc.

Centralized Deadlock Detection (Example Using Simple Algorithms)

- Cycle in global WFG ⇒ deadlock



- No cycle in global WFG ⇒ no deadlock

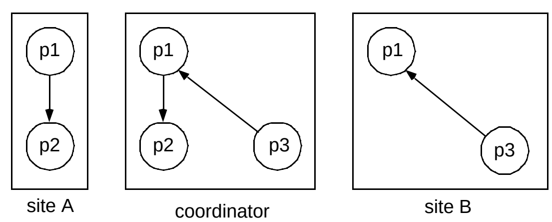


Centralized Deadlock Detection (Simple Algorithms) (cont.)

- Second Algorithm
  - A central coordinator maintains a global wait-for graph (WFG) for the system
    - Individual sites also maintain local WFGs for local processes and resources
    - Global WFG is an <u>approximation</u> of the total state of the system
  - When should the coordinator update the WFG and try to detect deadlocks?
    1. Whenever a new edge is inserted or removed in a local WFG
       - Site informs coordinator via a message
       - Global WFG can be slightly out-of-date
    2. Periodically, when a number of changes have been made to WFG
       - Site sends several changes at once
       - Global WFG can be more out-of-date
    3. Whenever it needs to detect deadlock
  - After deadlock is detected, coordinator selects a “victim”, and tells all the sites, which take the appropriate action

Centralized Deadlock Detection (Problem of False Deadlock)

- Consider this system state:



  - Now assume process p2 releases resource p1 is waiting on
  - Slightly thereafter, process p2 requests resource p3 is holding
  - However, first message reaches coordinator after second message
  - The global WFG now has a *false cycle,* which leads to a report of *false deadlock*
- Lamport’s algorithm can append logical clock values to each message and avoid this problem, although at the cost of many more messages (details in text)

Centralized Deadlock Detection (Ho and Ramamoorthy, 1982)

- Two-phase algorithm:
  - Every site maintains a status table, containing status of all local processes
    - Resources held, resources waiting on
  - Periodically, coordinator requests all status tables, builds a WFG, and searches it for cycles
    - No cycles $\Rightarrow$ no deadlock
    - If cycle is found, coordinator again requests all status tables, again builds a WFG, but this time uses only those edges common to both sets of status tables
  - Rationale was that by using information from two consecutive reports, coordinator would get a consistent view of the state
    - However, it was later shown that a deadlock in this WFG does not imply a deadlock exists
    - So, the HR-two-phase algorithm may reduce the possibility of reporting false deadlocks, but doesn't eliminate it

Centralized Deadlock Detection (Ho and Ramamoorthy) (cont.)

- One-phase algorithm:
  - Every site maintains two status tables
    - *Resource status table* keeps track of processes that are holding or requesting resources at that site
    - *Process status table* keeps track of resources requested or held by processes at that site
  - Periodically, coordinator requests all status tables, builds a WFG using only information in both a resource and process table, and searches it for cycles
  - Rationale was that this eliminates inconsistency caused by network delay
    - Message in transit will have entry at one site, not yet at the other
    - ✓ The HR-one-phase algorithm does not report false deadlocks
  - Compared to two-phase algorithm:
    - ✓ Faster, less messages
    - ✗ More storage (2 tables), bigger messages