TDDB68 + TDDE47 + TDDD82

Lecture:
Deadlocks

Mikael Asplund
Real-time Systems Laboratory
Department of Computer and Information Science

Thanks to Simin Nadjm-Tehrani and Christoph Kessler for much of the material behind these slides.

Reading guidelines

- Silberschatz et al.,
  - 9th edition: chapter 7 Deadlocks
  - 10th edition: chapter 8 Deadlocks

- Worth checking out:
  - https://github.com/angrave/SystemProgramming/wiki

Consider interleaving the following

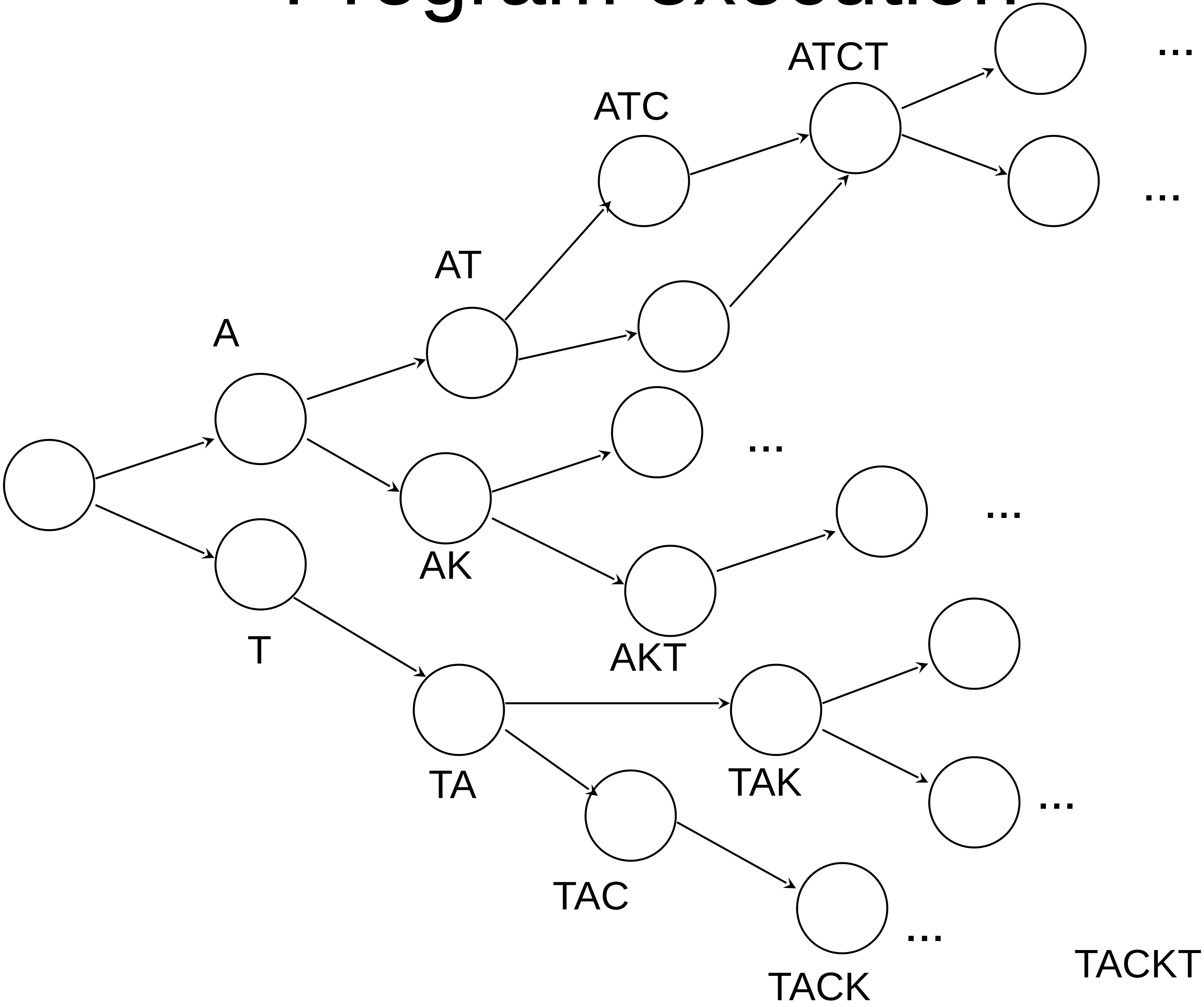
Process A

```
while true {
  print(A)
  print(K)
}
```

Process B

```
while true {
  print(T)
  print(C)
}
```

Program execution



Correctness properties

- Safety properties
  - Something **bad** will **not** happen

- Liveness properties
  - Something **good** will happen (eventually)

- More on this way of reasoning in the Software Verification course!

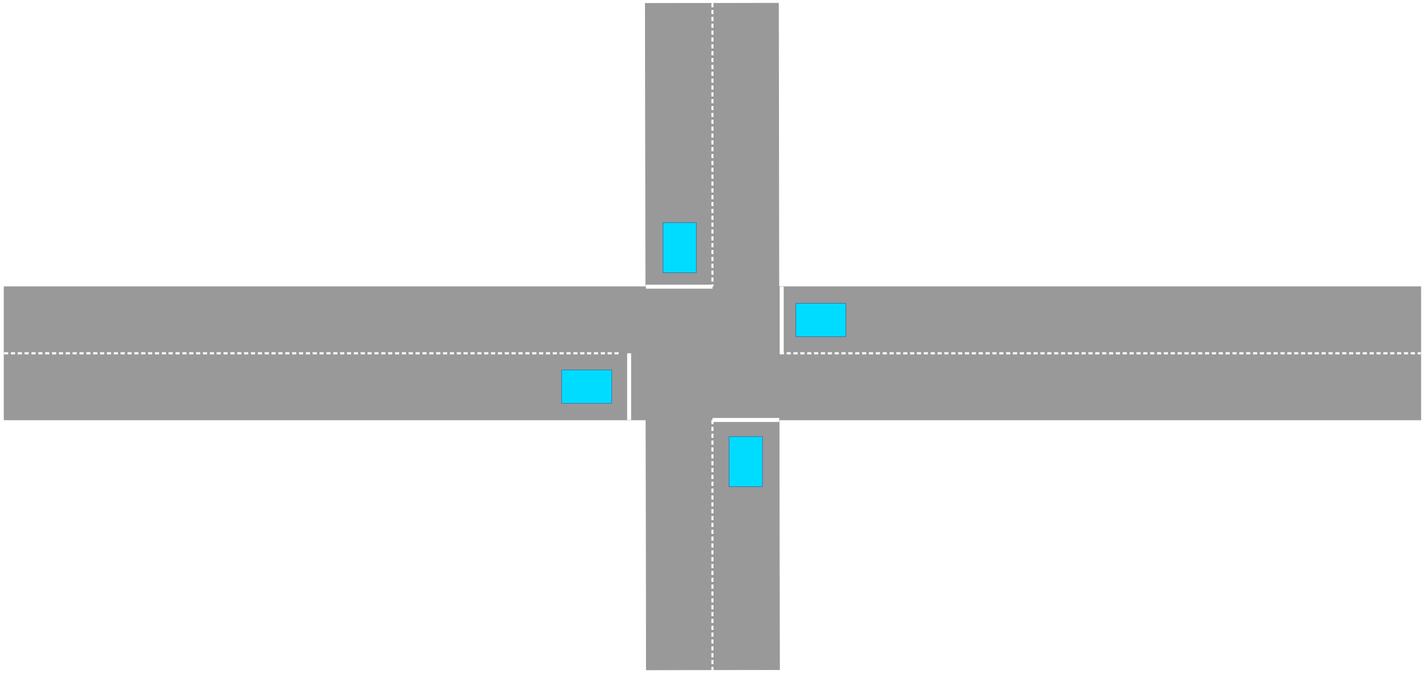
Progress

- A form of liveness

- Mathematically defined within a given system model
  - Can be defined on system or process level
  - Typically ensures that if system is in some state s, then it will reach some other state s' where some property P holds.

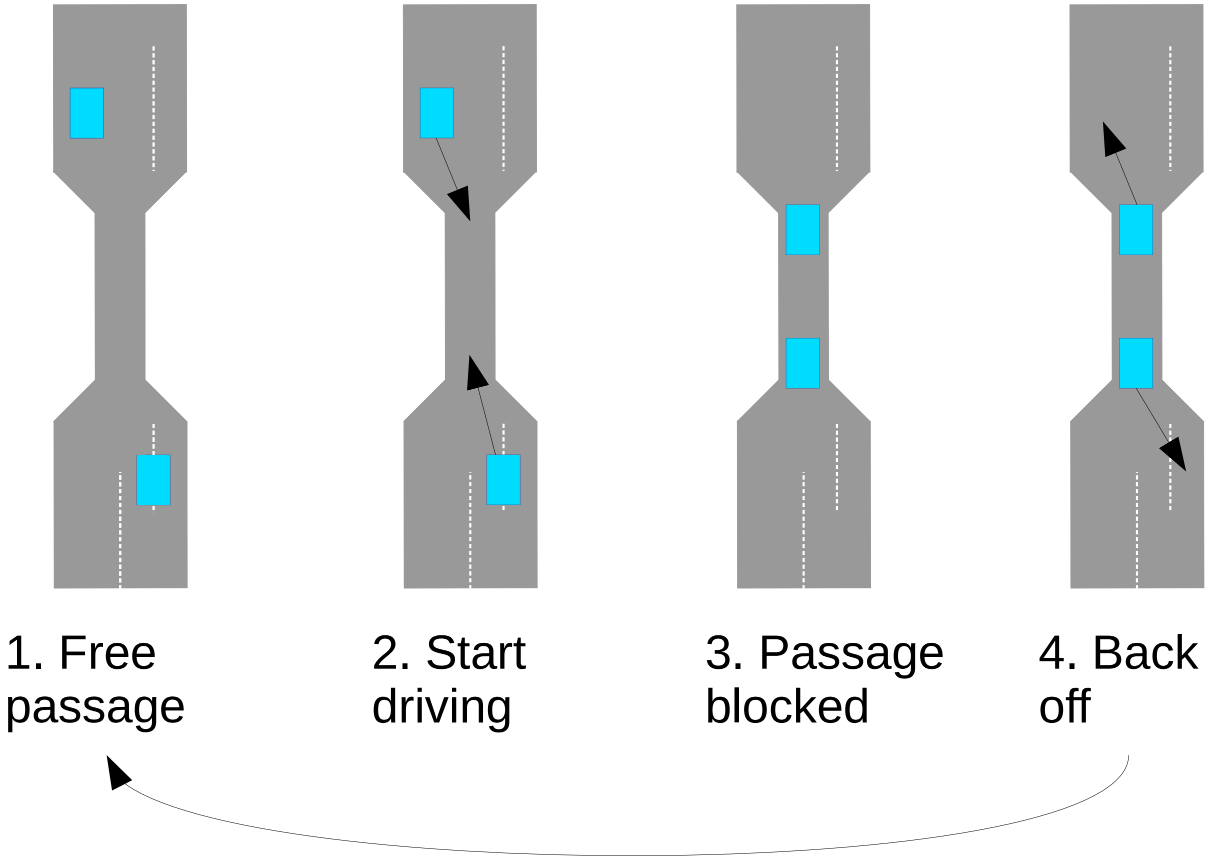
- Implies freedom from:
  - Deadlock
  - Livelock
  - (Starvation depending on the model)

Deadlock



Deadlock occurs when a group of processes are locked in a circular wait (more on this soon).

Livelock



1. Free passage
2. Start driving
3. Passage blocked
4. Back off

Livelock occurs when a group of processes are stuck in a loop of actions where they stop each other from progressing

Deadlock-freedom

- Freedom from deadlock is fundamental to any concurrent system

- Necessary but not sufficient for progress!

- Topic for the rest of this lecture

Earlier

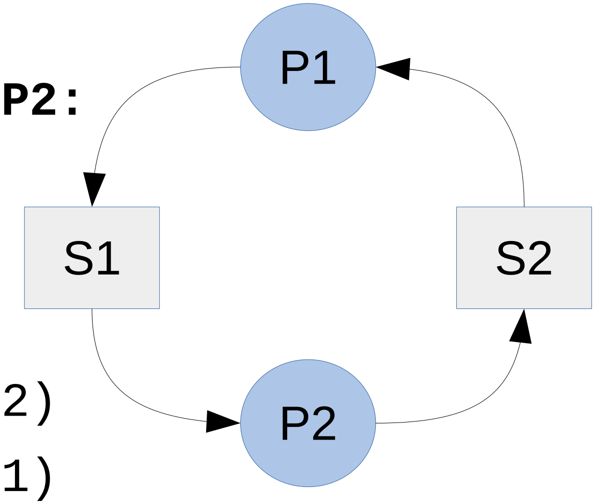
- Mutual exclusion and condition synchronisation
  - Semaphores
  - Monitors
  - Concurrent data structures

- Worked well for single resource

- What about multiple resources?

Simple deadlock situation

- Two semaphores
  - S1 for resource R1
  - S2 for resource R2



```
Process P2:
wait(S1)
wait(S2)
...
signal(S2)
signal(S1)
```

```
Process P1:
wait(S2)
wait(S1)
...
signal(S1)
signal(S2)
```

Coffman conditions

Four necessary conditions for deadlock:

1. Mutual exclusion

Access to a resource is limited to one (or a limited number of) process(es) at a time

2. Hold & wait

A process may hold a resource and wait for another resource at the same time

3. Voluntary release

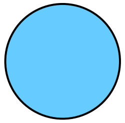
Resources can only be released by a process voluntarily

4. Circular wait

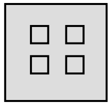
There is a chain of processes where each process holds a resource that is required by another process

Resource-Allocation Graph

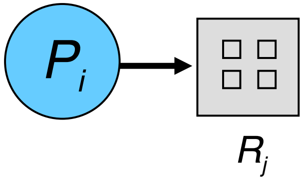
Process



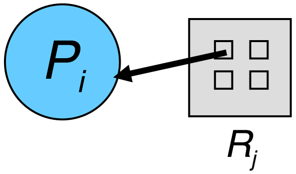
Resource type
with 4 instances



P_i requests an
instance of R_j

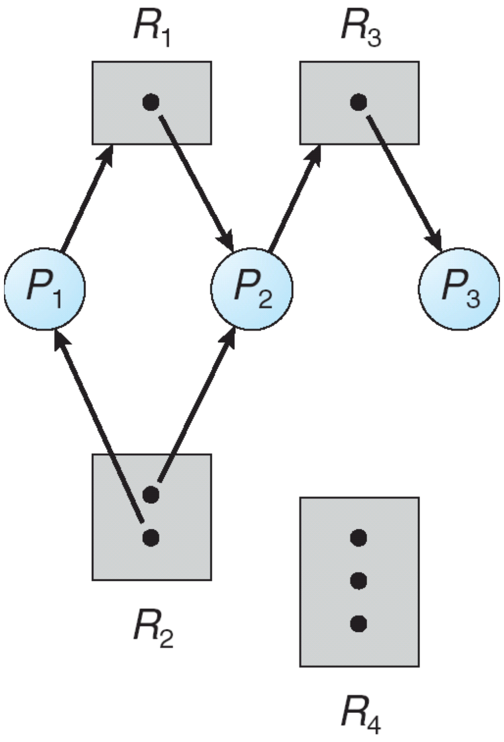


P_i is holding an
instance of R_j

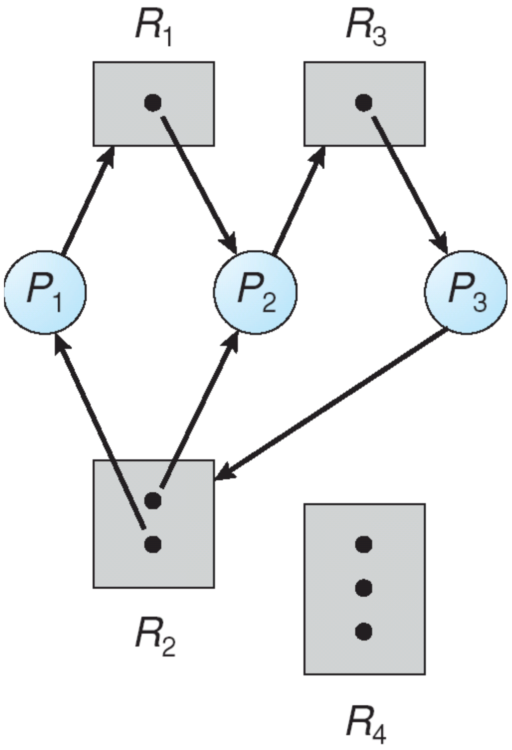


Which of these have a dealock?

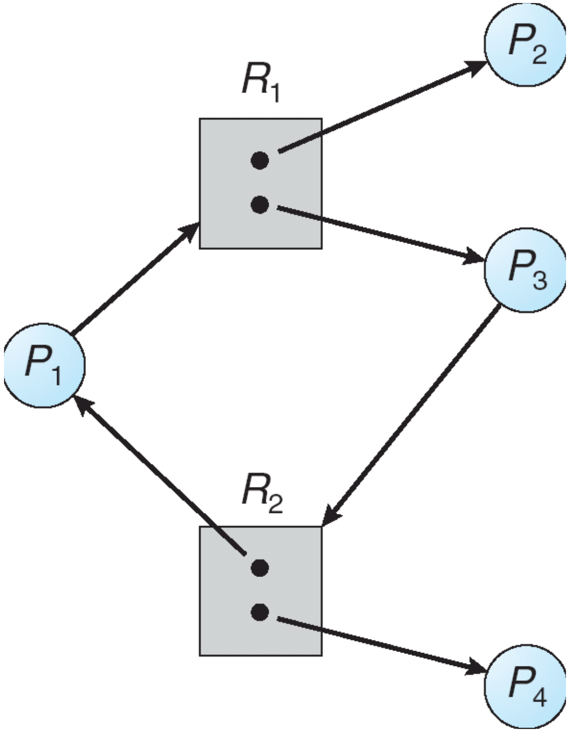
Menti code: 46 75 25



A



B



C

Basic Facts

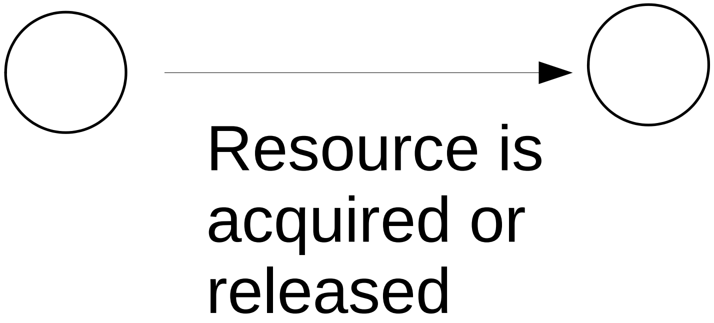
- Graph contains no cycles ⇒ no deadlock.
- Graph contains a cycle ⇒
  - if only one instance per resource type, then deadlock.
  - if several instances per resource type, *possibility* of deadlock.

Deadlock elimination

Four approaches:

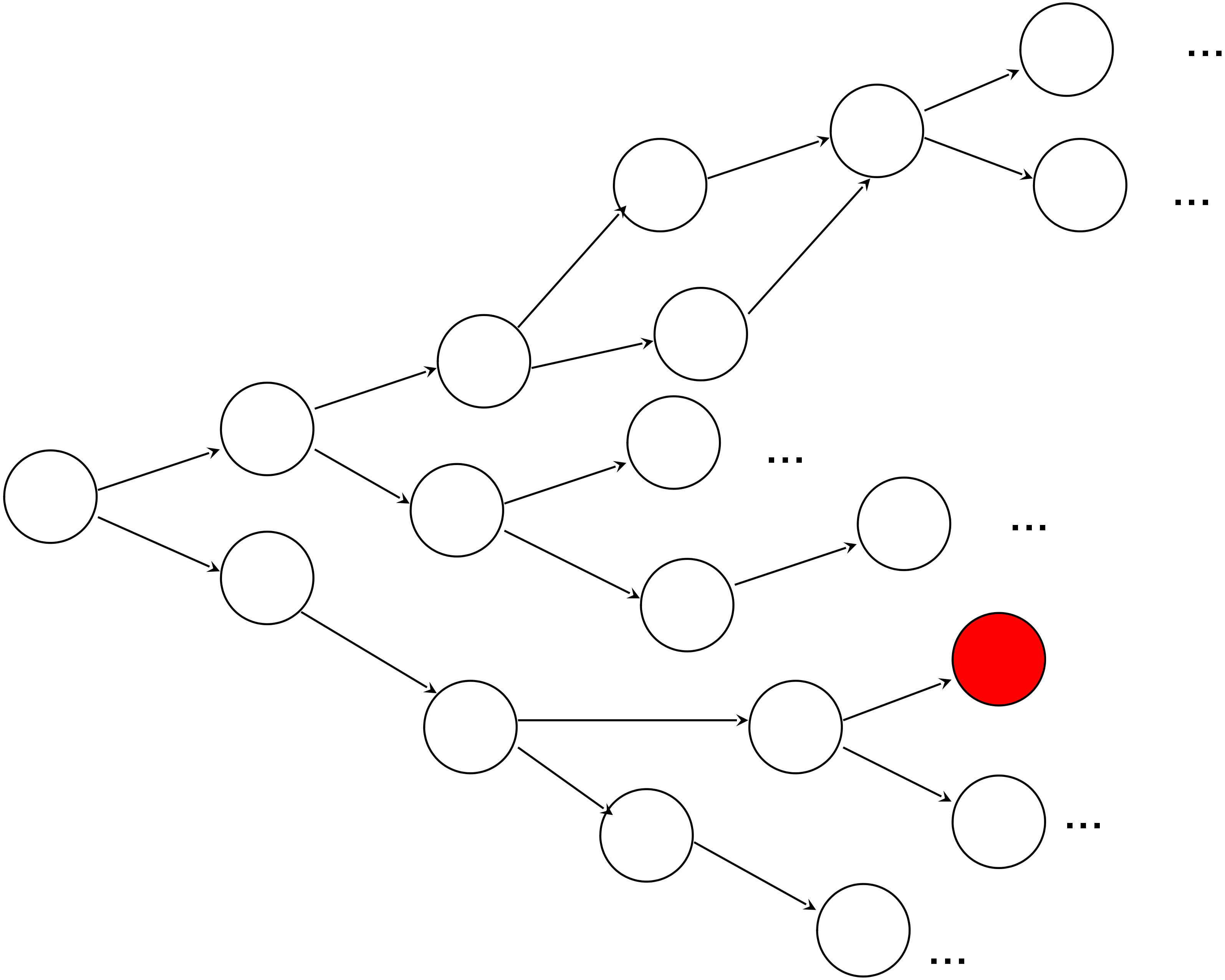
- Deadlock prevention
- Deadlock avoidance
- Deadlock detection and treatment
- Ignore the problem

State transition
(in terms of resources)

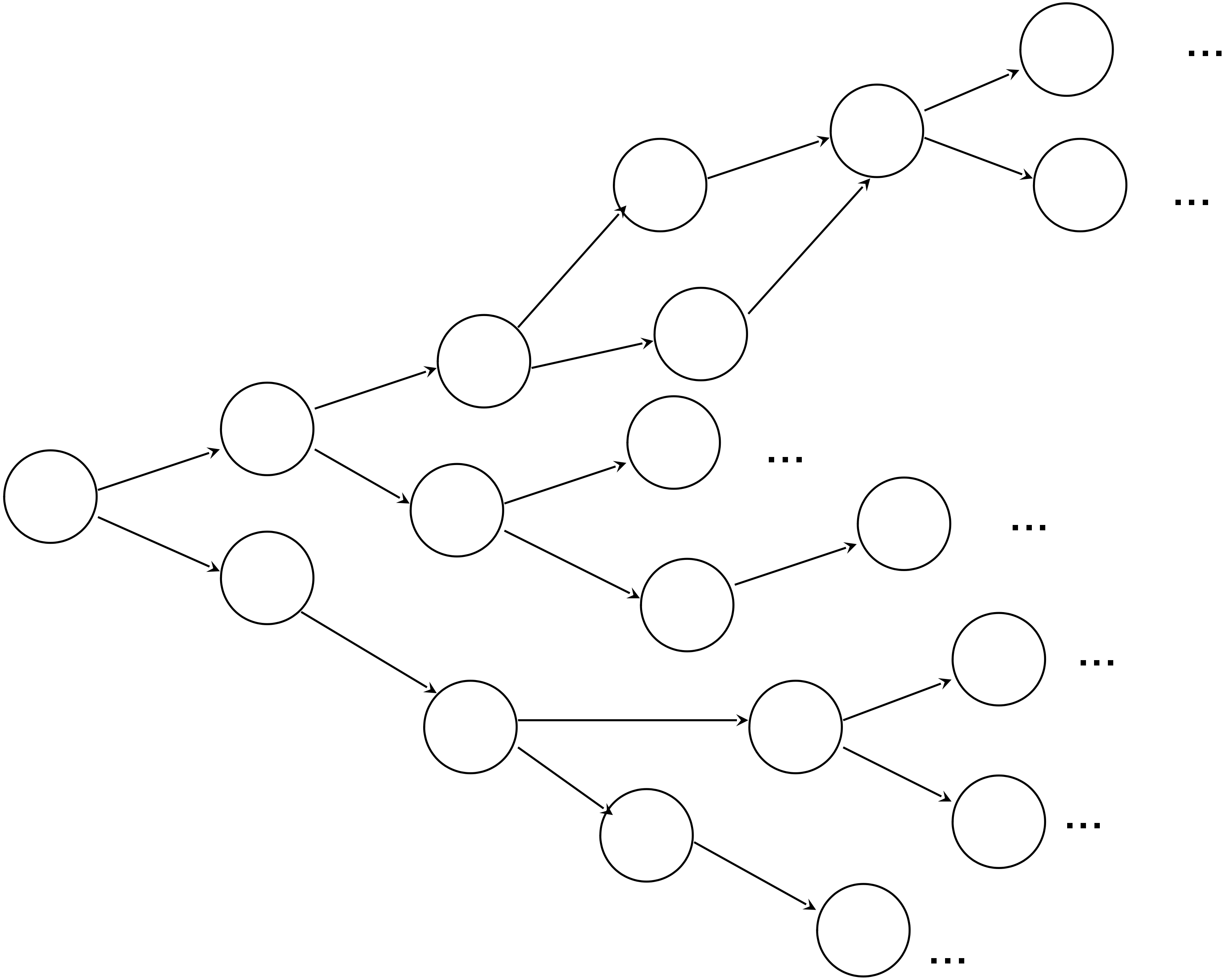


Resource is
acquired or
released

Program execution with deadlock



Deadlock prevention



Deadlock prevention:

Ensure that at least one of the Coffman conditions can never occur

Prevent mutual exclusion (ME)

- ME is needed only for *limited* shared resources

- Example: Read-only-file access by arbitrarily many readers
  - Readers-writer lock

Prevent Hold&Wait

- Whenever a process requests a resource, it cannot hold any other resources.

- Request all resources at once
  - Dining philosopher solution

- Low resource utilization; starvation possible; not flexible.

Ensure preemption

- Force another process to release its resources
- Preempted resources are added to the list of resources for which the process is waiting.
- Process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting.

Prevent circular wait

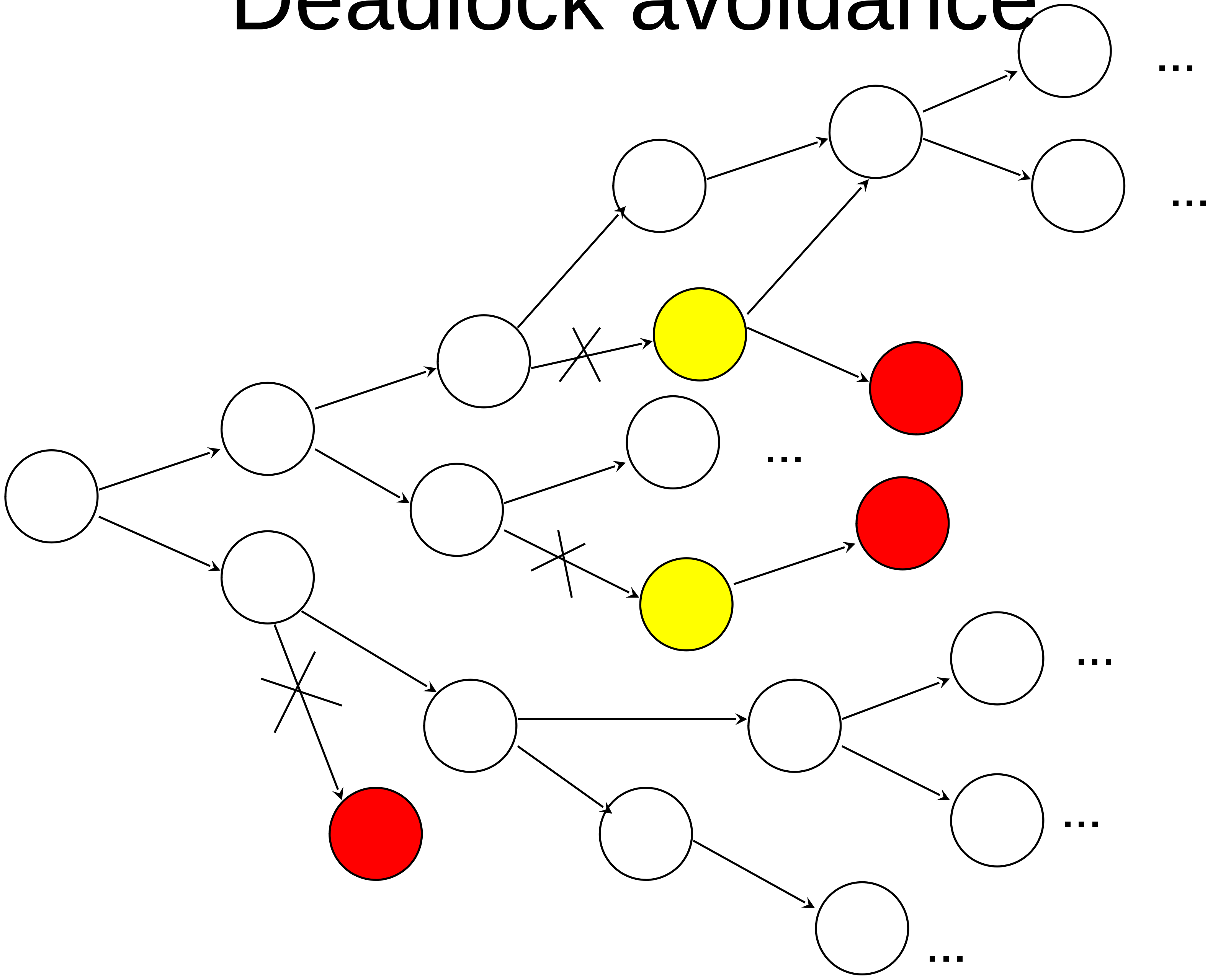
- Impose a *total ordering* of all resources
  - requests must be performed in this order.

- Priorities of processes and resources
  - e.g., Immediate Ceiling Protocol in Real-time scheduling

Tools to eliminate circular wait

- Windows driver verifier
- Linux lockdep tool
- Static analysis tools
  - Cbmc for pthreads (http://www.cprover.org/deadlock-detection/)

Deadlock avoidance

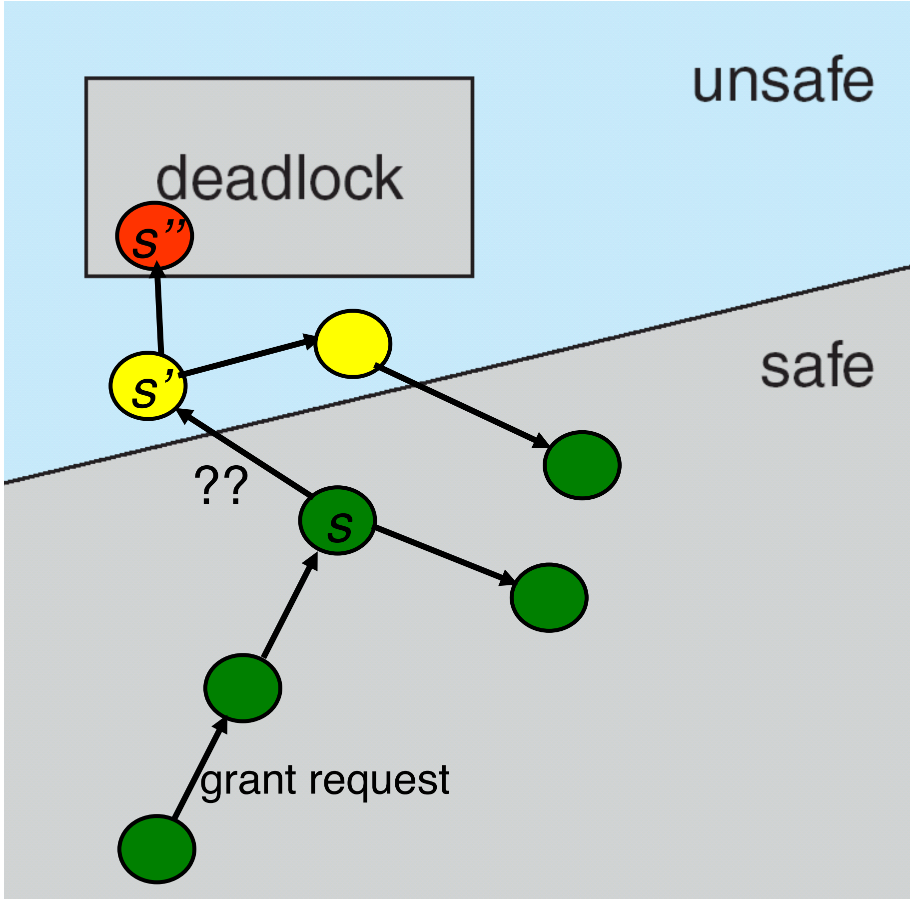


Safe state

System is in **safe state** if there *exists* a **safe sequence** (i.e., completion sequence) of *all* processes.

Safe states and deadlocks

- If a system is in safe state ⇒ no deadlocks.
- If a system is in unsafe state ⇒ *possibility* of deadlock.
- Avoidance:
  ensure that a system will never enter an unsafe state.



Assumptions

- Requires a priori knowledge of needed resources

- Assume that each process declare the amount of resources needed

Deadlock Avoidance Algorithms

Avoidance Algorithms for 2 Cases:

- Case 1: All resource types have 1 instance only
  - Resource Allocation Graph Algorithm
- Case 2: Multiple instances per resource type
  - Banker’s Algorithm

Banker’s algorithm

- Multiple instances of each resource

- Upon each process request
  - Check that the request is within the maximum limit for that process
  - Check that the new state is safe

Rejecting a request

- When allocating a request does not lead to a new “safe” state:
  - Refuse to grant

- The request can be repeated in some future state and get granted

Inputs and outputs of Banker's

- **Input:**
  - Matrix **Max**
  - Vector **Available**
  - Matrix **Allocation**
  - **Request**[i] for some process i (* **Request**[i] =< **Available** *)

- **Output**:
  - Yes + new state, or
  - No + unchanged state (Request[i] can not be allocated now)

Data structures

Let *n* = number of processes, and *m* = number of resources types.

Available*:* Vector of length *m*. If *Available[j]* = *k*, there are *k* instances of resource type R_j available

Max*: n x m* matrix. If *Max* [*i,j*] = *k*, then process *i* may request at most *k* instances of resource type R_j, *Max[i]* denotes the *i'th* row.

Allocation*:* *n* x *m* matrix. If *Allocation[i,j]* = *k* then *i* is currently allocated *k* instances of R_j, *Allocation[i]* denotes the *i'th* row.

Need*:* *n* x *m* matrix. If *Need*[*i,j*] = *k*, then *i* may need *k* more instances of R_j to complete its task, *Need[i]* denotes the *i'th* row.

Banker's algorithm

1. **Need** := **Max** – **Allocation**

    Check that **Request[i]** <= **Need[i]**

2. Check whether **Request**[i] <= **Available**

    if not, return ”No”

3. Pretend that resources in **Request**[i] are to be allocated, compute new state:

    Allocation’[i] := **Allocation**[i] + **Request**[i]

    Need’[i] := **Need**[i] - **Request**[i]

    Available’ := **Available** – **Request**[i]

4. Test whether the new state is deadlock-avoiding (denoted safe), in which case return ”Yes”.

    Otherwise, return ”No” - roll back to the old state.

Testing for safe state

- Start with a given **Allocation’** and check if it is safe (avoids future deadlocks) according to the 3-step algorithm.

Safety algorithm data structures

Finish: n vector with Boolean values (initially false)

Work : m vector denotes the changing resource set as the processes become ready and release resources (initially **Work** := **Available’**)

Safety algorithm

1. Check if there is some process i for which **Finish**[i] = false and for which **Need'**[i] <= **Work**. If there is no such process i, go to step 3.

2. Free the resources that i has used to get finished:

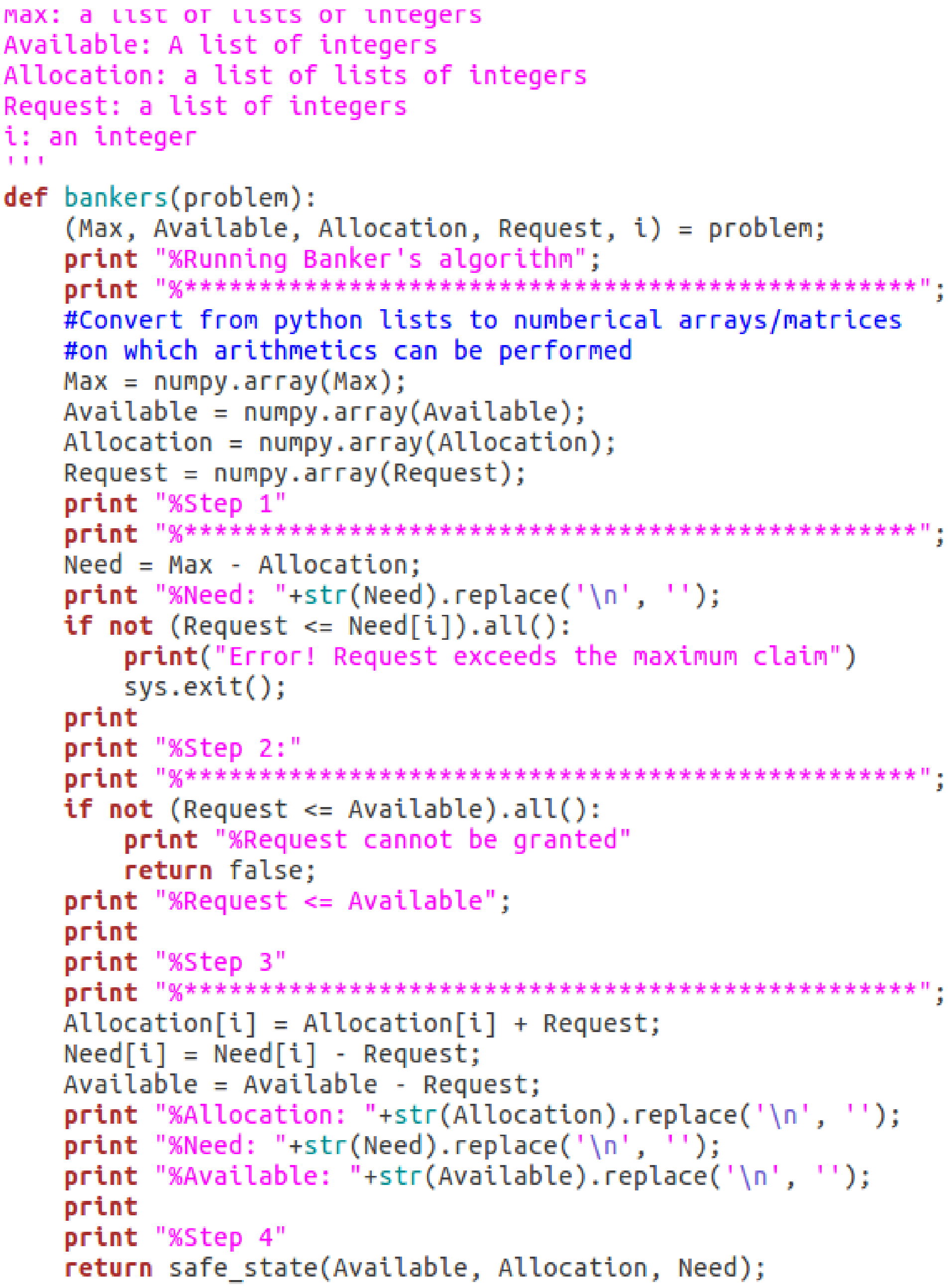
Work := **Work** + **Allocation'**[i]

Finish[i] := true

continue from step 1.

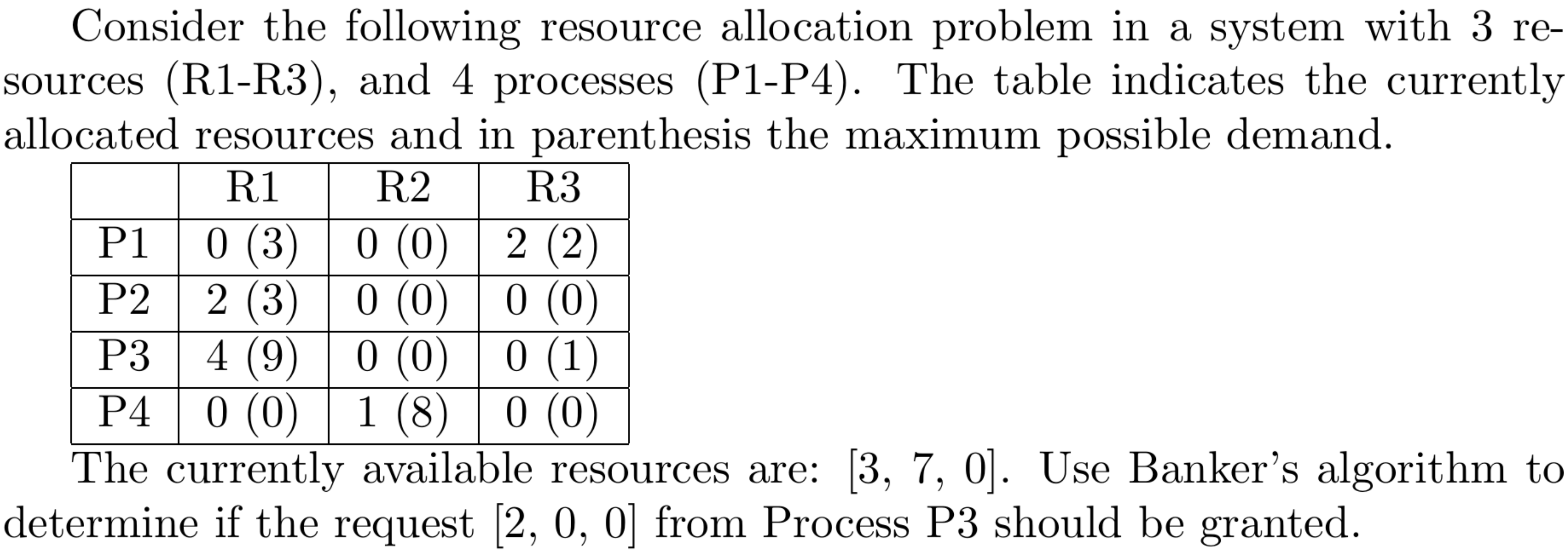
3. If **Finish**[i] = true for all i then the initial state is deadlock-avoiding, otherwise it is not.

Python code



```
Max: a list of lists of integers
Available: A list of integers
Allocation: a list of lists of integers
Request: a list of integers
i: an integer
'''
def bankers(problem):
    (Max, Available, Allocation, Request, i) = problem;
    print "%Running Banker's algorithm";
    print "%*****************************************************";
    #Convert from python lists to numberical arrays/matrices
    #on which arithmetics can be performed
    Max = numpy.array(Max);
    Available = numpy.array(Available);
    Allocation = numpy.array(Allocation);
    Request = numpy.array(Request);
    print "%Step 1"
    print "%*****************************************************";
    Need = Max - Allocation;
    print "%Need: "+str(Need).replace('\n', '');
    if not (Request <= Need[i]).all():
        print("Error! Request exceeds the maximum claim")
        sys.exit();
    print
    print "%Step 2:"
    print "%*****************************************************";
    if not (Request <= Available).all():
        print "%Request cannot be granted"
        return false;
    print "%Request <= Available";
    print
    print "%Step 3"
    print "%*****************************************************";
    Allocation[i] = Allocation[i] + Request;
    Need[i] = Need[i] - Request;
    Available = Available - Request;
    print "%Allocation: "+str(Allocation).replace('\n', '');
    print "%Need: "+str(Need).replace('\n', '');
    print "%Available: "+str(Available).replace('\n', '');
    print
    print "%Step 4"
    return safe_state(Available, Allocation, Need);
```

Generated problem



Consider the following resource allocation problem in a system with 3 resources (R1-R3), and 4 processes (P1-P4). The table indicates the currently allocated resources and in parenthesis the maximum possible demand.

	R1	R2	R3
P1	0 (3)	0 (0)	2 (2)
P2	2 (3)	0 (0)	0 (0)
P3	4 (9)	0 (0)	0 (1)
P4	0 (0)	1 (8)	0 (0)

The currently available resources are: [3, 7, 0]. Use Banker's algorithm to determine if the request [2, 0, 0] from Process P3 should be granted.

Weaknesses of Banker's algorithm?

Weaknesses of the Banker’s Algorithm

- Assumes a fixed number of resources
  - not realistic – number of resources can vary over time

- Assumes a fixed population of processes
  - not realistic for interactive systems

- Assumes that processes state maximum needs in advance
  - often not known
    (depend e.g. on input data or user commands)

- Waiting for completion of one or several processes may take very long / unpredictable time before a request is granted

Deadlock Detection and Recovery

- Allow system to enter deadlock state

- Detection algorithm
  - Single instance of each resource type
  - Multiple instances

- Recovery scheme

Menti question (46 75 25)

Which of the following statements are true about deadlocks?:

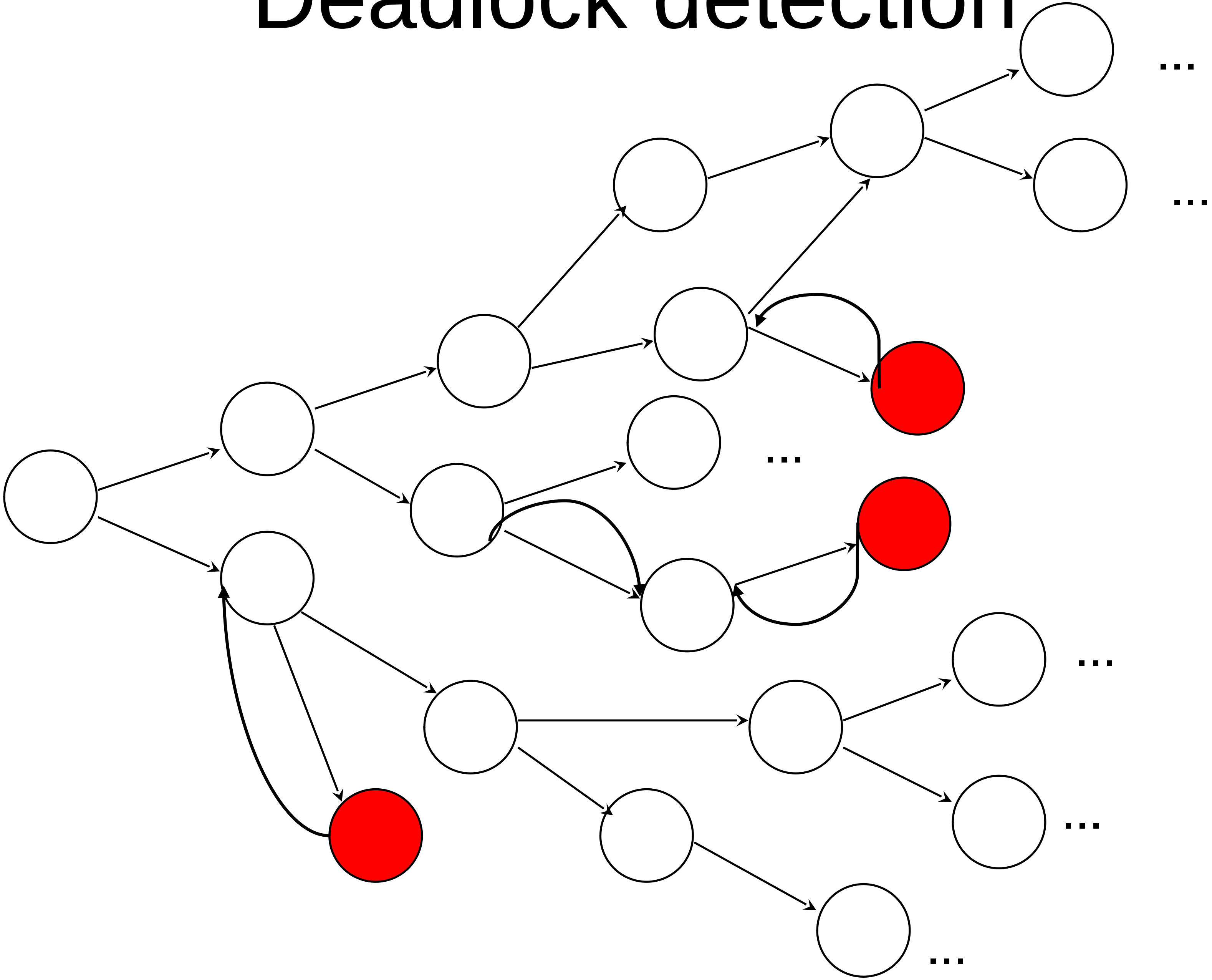
A. If there is only a single instance of every resource, a cycle in the resource allocation graph means that there is a deadlock.

B. All four Coffman conditions must me met for there to be a deadlock.

C. Banker's algorithm is used to detect and remove deadlocks.

D. Banker's algorithm guarantees freedom from starvation.

Deadlock detection

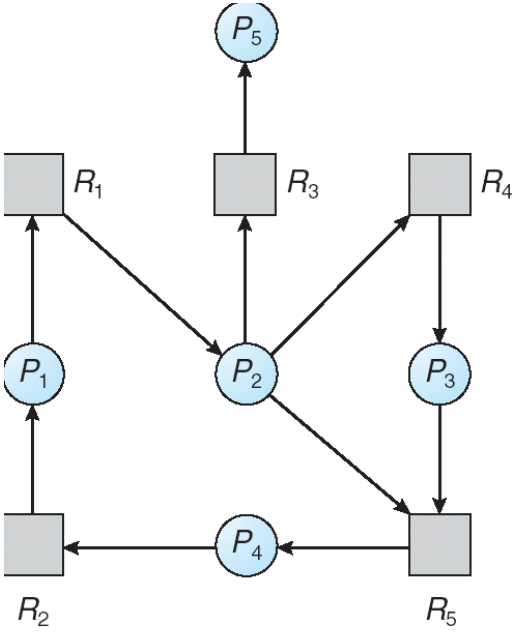


Deadlock detection with **single** instance resources

Search for cycle in wait-for graph

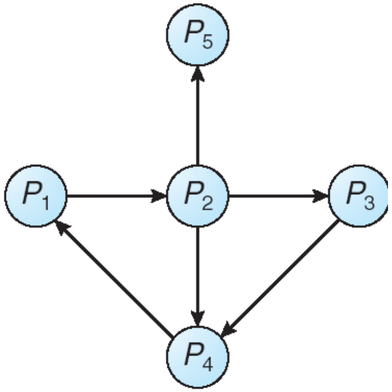
- Maintain ***wait-for* graph**
  - Nodes are processes.
  - $P_i \rightarrow P_j$
    iff P_i is waiting for P_j.

- Periodically invoke an algorithm
  that searches for a cycle in the graph.



(a)

Resource-Allocation Graph



(b)

Corresponding
wait-for graph

Deadlock detection with **multiple** instance resources

Detection Algorithm [Coffman et al. 1971]

1. Vectors ***Work***[1..*m*], ***Finish***[1..*n*] initialized by:

   $Work = Available$

   for $i = 1, 2, \ldots, n$, **if** $Allocation_i \neq 0$ **then** $Finish[i] = false$
   otherwise $Finish[i] = true$

2. Find an index *i* such that both:

   (a) $Finish[i] == false$

   (b) $Request_i \leq Work$

   If no such *i* exists, **go to** step 4.

3. $Work = Work + Allocation_i$
   $Finish[i] = true$
   go to step 2.

4. **If** $Finish[i] == false$, for some i, $1 \leq i \leq n$,
   then the system is in deadlock state.
   Specifically, if $Finish[i] == false$, then P_i is deadlocked.

Difference to Banker's algorithm

- What is a safe state?
  - Consider the actual request (optimistically), not the maximum needs

- Reason: We compute if there is a deadlock **now**, not if one may happen later.

Example of Detection Algorithm

- 5 processes P_0 … P_4
- 3 resource types:
  A (7 instances), *B* (2 instances), *C* (6 instances)
- Snapshot at time T_0:

	Allocation			**Request**			**Available**		
	A	***B***	***C***	***A***	***B***	***C***	***A***	***B***	***C***
P_0	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
P_1	**2**	**0**	**0**	**2**	**0**	**2**			
P_2	**3**	**0**	**3**	**0**	**0**	**0**			
P_3	**2**	**1**	**1**	**1**	**0**	**0**			
P_4	**0**	**0**	**2**	**0**	**0**	**2**			

- Sequence <P_0, P_2, P_3, P_1, P_4> yields *Finish*[*i*] = true for all *i*.

Example (Cont.)

- P_2 requests an additional instance of type C.

	Allocation			Request			Available		
	A	B	C	A	B	C	A	B	C
P_0	0	1	0	0	0	0	0	0	0
P_1	2	0	0	2	0	2			
P_2	3	0	3	0	0	1			
P_3	2	1	1	1	0	0			
P_4	0	0	2	0	0	2			

- State of system?
  - Can reclaim resources held by process P_0, but insufficient resources to fulfill other process’ requests.
  - Deadlock exists, consisting of processes P_1, P_2, P_3, P_4.

Detection-Algorithm Usage

- When, and how often, to invoke depends on:
  - How often a deadlock is likely to occur?
  - How many processes will need to be rolled back?
    - one for each disjoint cycle
- Invocation at every resource request?
  - Too much overhead
- Occasional invocation?
(e.g., once per hour, or whenever CPU utilization below 40%)

Recovery from Deadlock: Process Termination

- Abort all deadlocked processes.

- Abort one process at a time until the deadlock cycle is eliminated.

- In which order should we choose to abort?
  - Priority of the process.
  - How long process has computed,
    and how much longer to completion.
  - Resources the process has used.
  - Resources the process needs to complete.
  - How many processes will need to be terminated.

Summary

- Deadlock characterization
  - 4 necessary conditions (Coffman)
  - Resource allocation graph

- Deadlock prevention
  - Prohibit one of the four necessary conditions

- Deadlock avoidance
  - 1 instance-resources: Resource allocation graph algorithm
  - Banker’s algorithm (state safety, request granting)

- Deadlock detection and recovery
  - 1 instance-resources: Find cycles in Wait-for graph
  - Several instances: Deadlock detection algorithm

- Do nothing – lift the problem to the user / programmer