Resource Allocation and Deadlock Handling

What’s in a deadlock

Deadlock: A set of blocked processes each waiting for an event (e.g. a resource to become available) that only another process in the set can cause

Examples of (potential) Deadlocks in Resource Allocation

- semaphores *A* and *B*, initialized to 1 (or: system has 2 tape drives; P_0 and P_1 each hold one tape drive and each needs another one)

P_0	P_1
wait (A);	*wait(B);*
wait (B);	*wait(A)*

- 200Kbytes memory-space is available

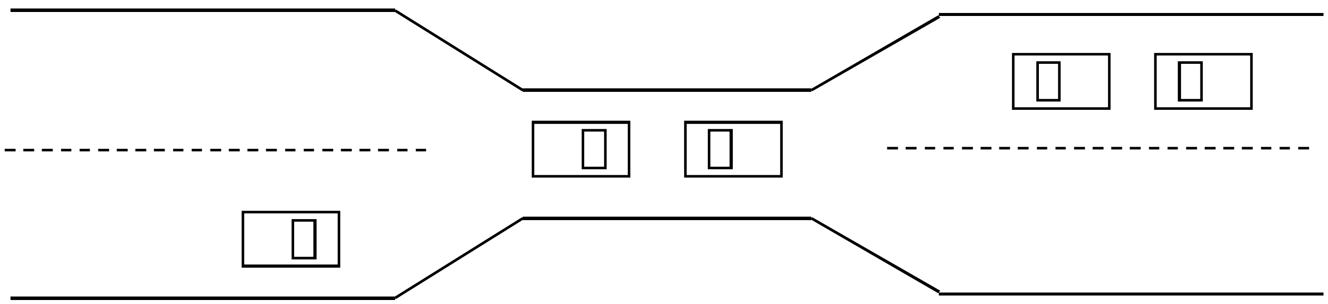
P_0	P_1
request (80Kbytes);	*request (80Kbytes);*
...	*...*
request (70Kbytes);	*request (70Kbytes);*

deadlock might occur if both processes progress to the second request

- message-passing with blocking receive

P_0	P_1
receive(P_1);	*receive(P_0);*
send(P_1, M1);	*send(P_0 , M0);*

Bridge Crossing Example



- Traffic only in one direction.
- Each “half” of the bridge can be viewed as a resource.

- If a deadlock occurs, it can be resolved if one car backs up (preempt resources and rollback).
  - several cars may have to be backed up
  - starvation is possible.

Conditions for Deadlock

[Coffman-etal 1971] **4 conditions must hold simultaneously** for a deadlock to occur:

- **Mutual exclusion:** only one process at a time can use a resource.
- **Hold and wait:** a process holding some resource can request additional resources and wait for them if they are held by other processes.
- **No preemption:** a resource can only be released voluntarily by the process holding it, after that process has completed its task.
  - Q: examples preemptable/non-preemtable resources?
- **Circular wait:** there exists a circular chain of 2 or more blocked processes, each waiting for a resource held by the next process in the chain

Resource Allocation & Handling of Deadlocks

- Structurally restrict the way in which processes request resources
  - deadlock *prevention*: deadlock *is not* possible

- Require processes to give advance info about the (max) resources they will require; then schedule processes in a way that avoids deadlock.
  - deadlock *avoidance*: deadlock *is* possible, but OS uses advance info to avoid it

- Allow a deadlock state and then *recover*

- Ignore the problem and pretend that deadlocks never occur in the system (can be a "solution" sometimes?!...)

Resource Allocation with Deadlock Prevention

Restrain the ways requests can be made; attack at least one of the 4 conditions, so that deadlocks are impossible to happen:

- **Mutual Exclusion** – (cannot do much here ...)
- **Hold and Wait** – must guarantee that when a process requests a resource, it does not hold any other resources.
  - Require process to request and be allocated all its resources at once or allow process to request resources only when the process has none.
  - Low resource utilization; starvation possible.
- **No Preemption** – If a process holding some resources requests another resource that cannot be immediately allocated, it releases the held resources and has to request them again (risk for starvation).
- **Circular Wait** – impose total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration (e.g first the tape, then the disk).

- Examples?

Fight the circular wait: Dining philosophers example

request forks in increasing fork-id

var f[0..n]: bin-semaphore /init all 1 /

```
P_i: (i!=n)
Repeat
    Wait(f[i])
    Wait(f[(i+1)modn])

    Eat

    Signal(f[(i+1)modn])
    Signal(f[i])

    Think
forever
```

```
Pn
Repeat
    Wait(f[(i+1)modn])
    Wait(f[i])

    Eat

    Signal(f[i])
    Signal(f[(i+1)modn])

    Think
forever
```

Fight the hold and wait: Dining philosophers example

semaphore S[N]

int state[N]

Pi: do

<think>

take_forks(i)

<eat>

leave_forks(i)

forever

take_forks(i)

wait(mutex)

state(i) := HUNGRY

test(i)

signal(mutex)

wait(S[i])

leave_forks(i)

wait(mutex)

state(i) := THINKING

test(left(i))

test(right(i)

signal(mutex)

test(i)

if state(i) ==HUNGRY && state(left(i)) != EATING && state(left(i)) != EATING then

state(i) := EATING

signal(S[i])

Fight the no-preemption: Dining philosophers example

```
var f[0..n]: record
     s: bin-semaphore
     available: boolean /init all 1 /
P_i:
Repeat
    While <not holding both forks> do
        Lock(f[i])
        If !trylock(f[(i+1)modn]) then release f[i];
    od
        Eat
    Release(f[i])
    Release(f[(i+1)modn])
    Think
forever
```

```
trylock(fork)
wait(fork.s)
     If fork.available then
        fork.available := false
          ret:= true
     else ret:= false
     Return(ret)
Signal(fork.s)
```

```
Lock(fork)
Repeat
Until (trylock(fork))
```

System Model

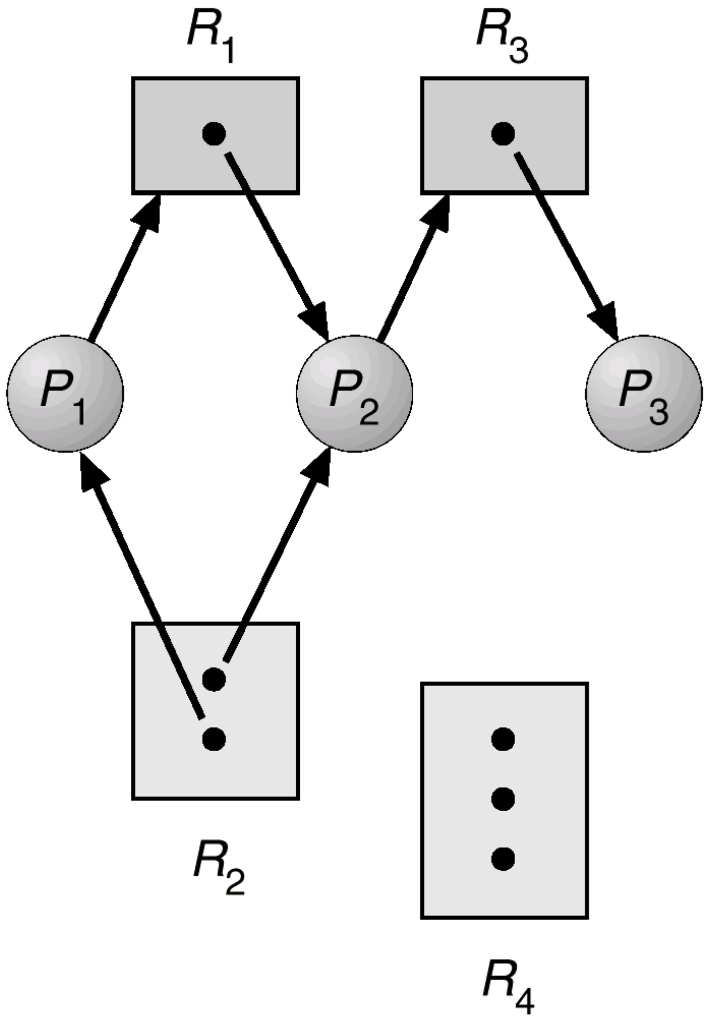
- Resource types $R_1, R_2, \ldots, R_m$
  - *e.g. CPU, memory space, I/O devices, files*
  - each resource type R_i has W_i instances.
- Each process utilizes a resource as follows:
  - request
  - use
  - release

Resource-Allocation Graph

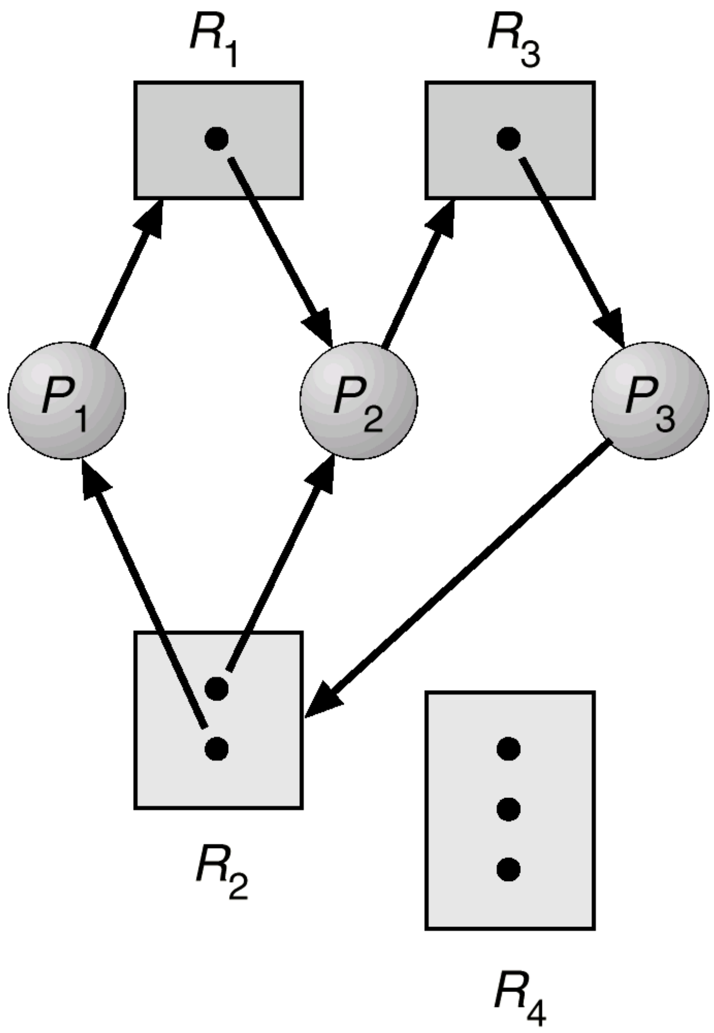
A set of vertices V and a set of edges E.

- V is partitioned into two sets:
  - $P = \{P_1, P_2, \ldots, P_n\}$ the set of processes
  - $R = \{R_1, R_2, \ldots, R_m\}$ the set of resource types
- request edge: $P_i \rightarrow R_j$
- assignment edge: $R_j \rightarrow P_i$

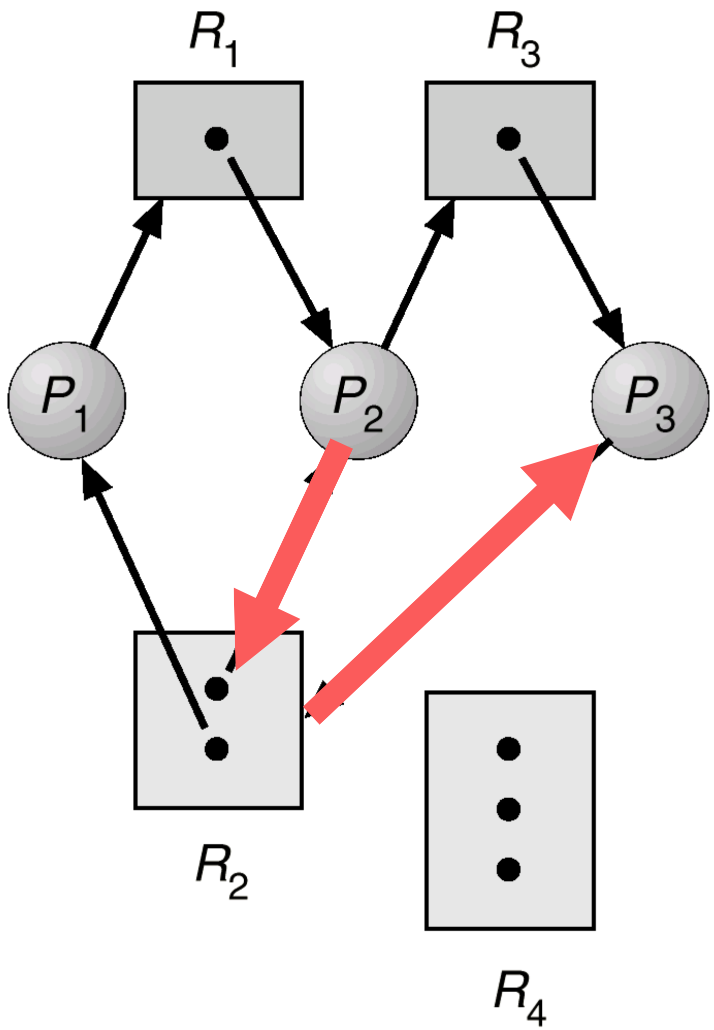
Example of a Resource Allocation Graph



Resource Allocation Graph With A Deadlock



Resource Allocation Graph With A cycle but no Deadlock



Basic Facts

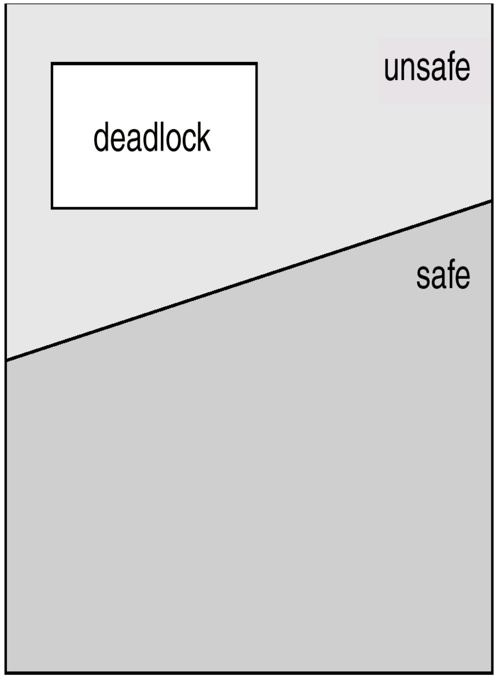
- graph contains no cycles ⇒ no deadlock.
  (i.e. cycle is always a necessary condition for deadlock)

- If graph contains a cycle ⇒
  - if one instance per resource type, then deadlock.
  - if several instances per resource type, then possibility of deadlock
    - Thm: if immediate-allocation-method, then knot ⇒ deadlock.
      - Knot= knot – strongly connected subgraph (no sinks) with no outgoing edges

Resource Allocation with Deadlock Avoidance

Requires *a priori information* available.

- e.g.: each *process* declares *maximum number of resources* of each type that it *may need* (e.g memory/disk pages).



Deadlock-avoidance algo:

- examines the resource-allocation state…
  - *available and allocated resources*
  - *maximum possible demands* of the processes.
- …to ensure there is *no potential for a circular-wait*:
  - safe state ⇒ no deadlocks in the horizon.
  - unsafe state ⇒ deadlock might occur (later…)
  - Q: how to do the safety check?

- *Avoidance* = ensure that *system will not enter an unsafe* state.

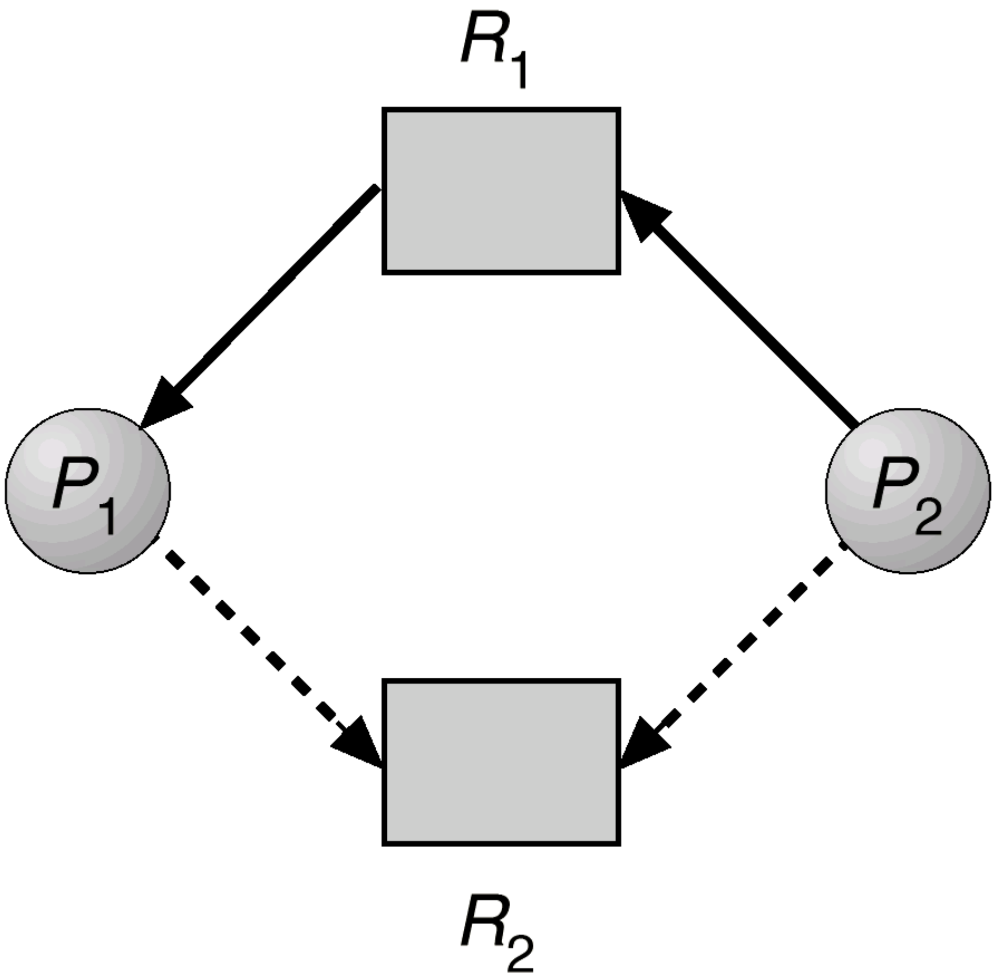
  Idea: If *satisfying a request* will result in an *unsafe state*, the *requesting process is suspended until enough resources are free-ed* by processes that will terminate in the meanwhile.

Enhanced Resource Allocation Graph for Deadlock Avoidance

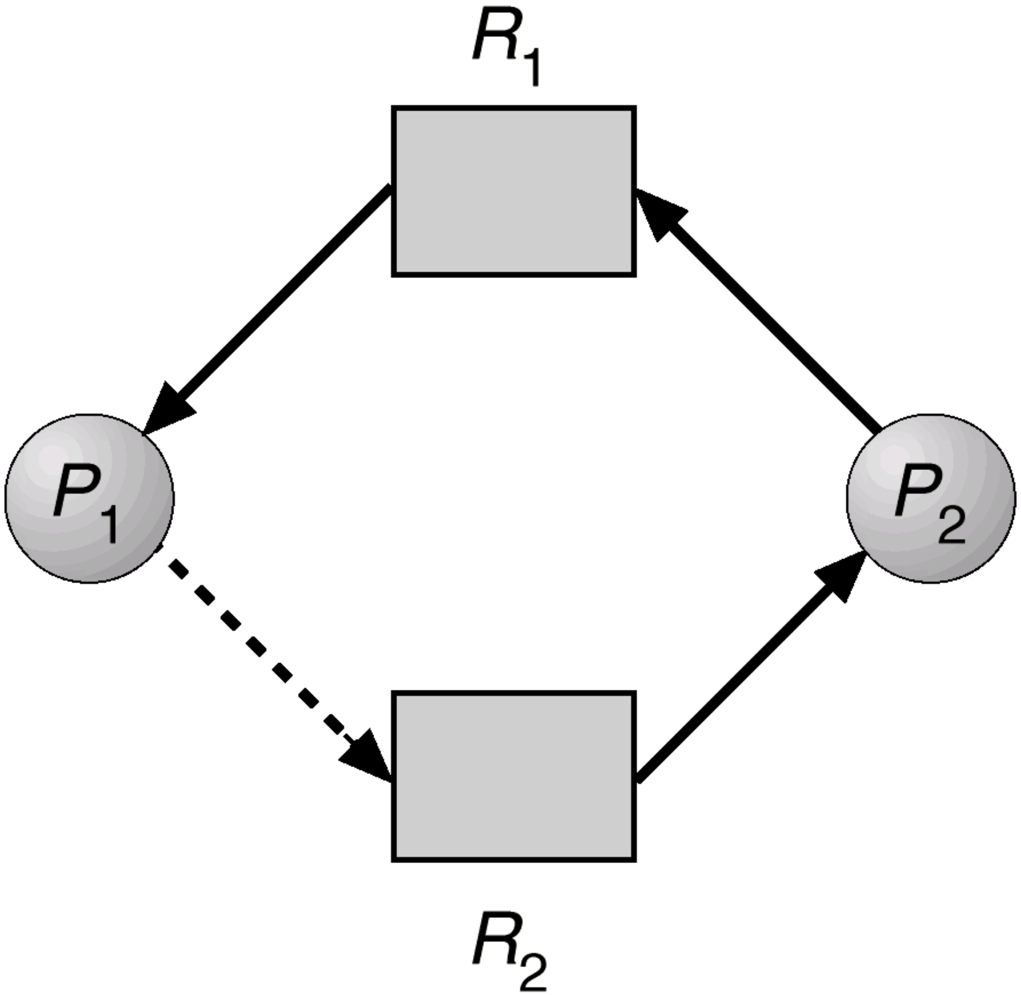
- *Claim edge* $P_i \rightarrow R_j$: P_j may request resource R_j
  - represented by a dashed line.
- Claim edge converts to request edge when a process requests a resource.
- When a resource is released by a process, assignment edge reconverts to a claim edge.

- Resources must be claimed *a priori* in the system.

Example Resource-Allocation Graph For Deadlock Avoidance: Safe State



Example Resource-Allocation Graph For Deadlock Avoidance: Unsafe State



Safety checking: More on Safe State

safe state = there exists a *safe sequence* $<P_1, P_2, \ldots, P_n>$ of terminating all processes:

for each P_i, the requests that it can still make can be granted by currently available resources + those held by $P_1, P_2, \ldots, P_{i-1}$

- The system can schedule the processes as follows:
  - if P_i 's resource needs are not immediately available, then it can
    - wait until all $P_1, P_2, \ldots, P_{i-1}$ have finished
    - obtain needed resources, execute, release resources, terminate.
  - then the next process can obtain its needed resources, and so on.

Banker's Algorithm for Resource Allocation with Deadlock Avoidance

Data Structures:

- *Max: n x m* matrix.
  - *Max* [*i,j*] = *k*: P_i may request max *k* instances of resource type R_j.
- *Allocation: n x m* matrix.
  - Allocation[*i,j*] = *k:* P_i is currently allocated *k* instances of R_j.
- *Available:* length *m* vector
  - available [*j*] = *k : k* instances of resource type R_j available.
- *Need: n x m* matrix:
  - *Need* [*i,j]* = *Max*[*i,j*] – *Allocation*[*i,j*]: potential max request by P_i for resource type R_j

RECALL: *Avoidance* = ensure that *system will not enter an unsafe* state.

Idea:

If *satisfying a request* will result in an *unsafe state*,

then *requesting process is suspended*

until enough resources are free-ed by processes that will terminate in the meanwhile.

Banker's algorithm: Resource Allocation

For each new *Request*$_i$ do /**Request*$_i$ [j] = k: P_i wants k instances of R_j. */

/* Check consequence if request is granted */

remember the current resource-allocation state;

Available := Available - Request$_{\boldsymbol{i}}$*;*

Allocation$_i$:= *Allocation*$_{\boldsymbol{i}}$ + *Request*$_{\boldsymbol{i}}$;

Need$_i$:= *Need*$_{\boldsymbol{i}}$ – *Request*$_{\boldsymbol{i}}$;;

If $\boxed{\textit{safety-check OK}}$ $\Rightarrow$ *the resources are allocated to* $P_{\boldsymbol{i}}$.

Else (unsafe) $\Rightarrow$

P_i *must wait and*

the old resource-allocation state is restored;

Banker's Algorithm: safety check

- *Work* and *Finish*: auxiliary vectors of length *m* and *n*, respectively.
- Initialize:

  Work := *Available*

  Finish [*i*] = *false* for *i* = 1,2, ..., *n.*

- While there exists *i* such that both do

  (a) *Finish* [*i*] = *false*
  (b) $Need_i \leq Work$.

  Work := *Work* + $Allocation_i$

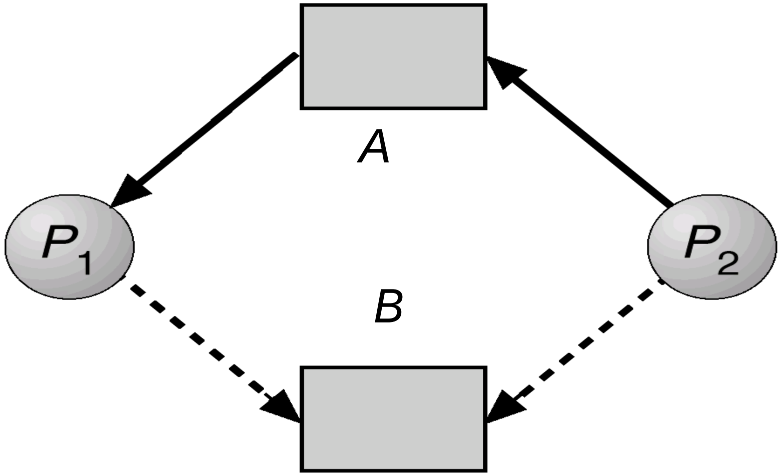
  Finish[*i*] := *true*

- If *Finish* [*i*] = true for all *i*, then the system is in a safe state else state is unsafe

Very simple example execution of Bankers Algo (snapshot 1)

	Allocation	*Max*	*Need*	*Available*
	A B	*A B*	*A B*	*A B*
P_1	1 0	1 1	0 1	0 1
P_2	0 0	1 1	1 1	

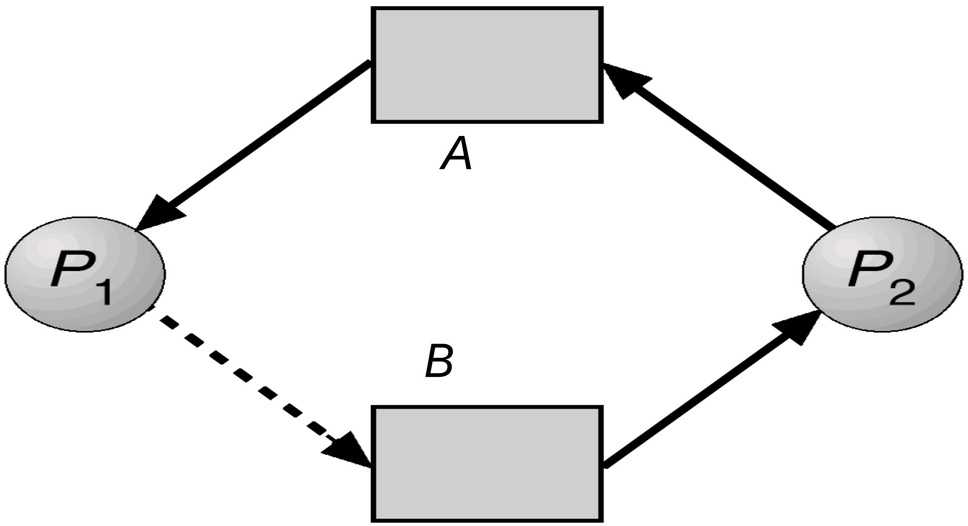
- The system is in a safe state since the sequence < P_1, P_2> satisfies safety criteria.



Very simple example execution of Bankers Algo (snapshot 2)

	Allocation	*Max*	*Need*	*Available*
	A B	*A B*	*A B*	*A B*
P_1	1 0	1 1	0 1	0 0
P_2	0 1	1 1	1 0	

- Allocating B to P_2 leaves the system in an unsafe state since there is no sequence that satisfies safety criteria (*Available* vector is 0 !).



Another example of Banker's Algorithm

- 5 processes P_0 through P_4; 3 resource types *A* (10 instances), *B* (5 instances), and *C* (7 instances).
- Snapshot at time T_0:

	Allocation	*Max*	*Need*	*Available*
	A B C	*A B C*	*A B C*	*A B C*
P_0	0 1 0	7 5 3	7 4 3	3 3 2
P_1	2 0 0	3 2 2	1 2 2	
P_2	3 0 2	9 0 2	6 0 0	
P_3	2 1 1	2 2 2	0 1 1	
P_4	0 0 2	4 3 3	4 3 1	

- The system is in a safe state since the sequence < P_1, P_3, P_4, P_2, P_0> satisfies safety criteria.

Another example (Cont.): P_1 request (1,0,2)

- Check that Request ≤ Available (that is, (1,0,2) ≤ (3,3,2) ⇒ *true.*

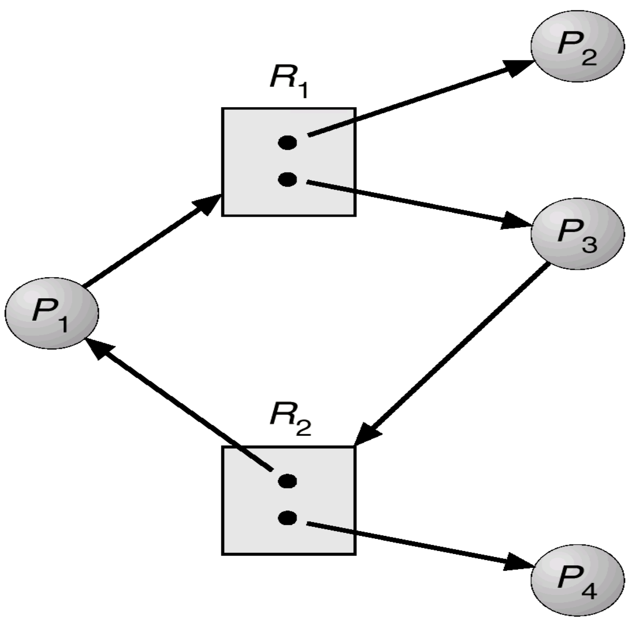
	Allocation	*Need*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	7 4 3	2 3 0
P_1	3 0 2	0 2 0	
P_2	3 0 1	6 0 0	
P_3	2 1 1	0 1 1	
P_4	0 0 2	4 3 1	

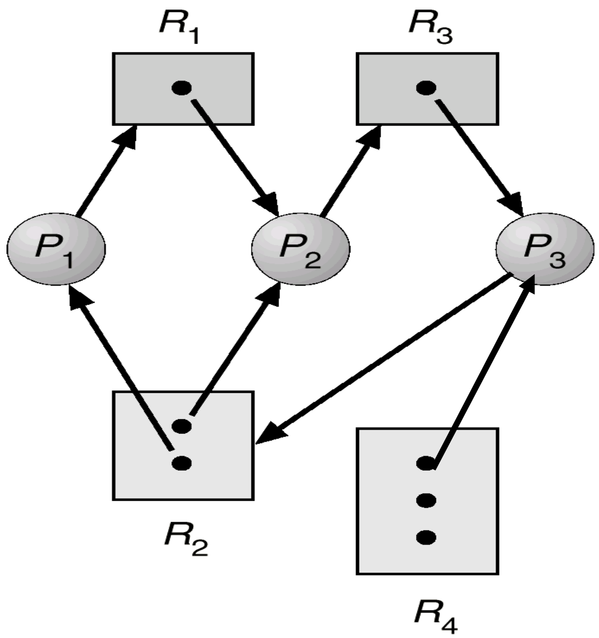
- Executing safety algorithm shows that sequence $\langle P_1, P_3, P_4, P_0, P_2 \rangle$ satisfies safety requirement.
- Can request for (3,3,0) by P_4 be granted?
- Can request for (0,2,0) by P_0 be granted?

Safety check using the ENHANCED resource allocation graph:

an algorithm that searches for cycles (knots) in the resource-allocation graph:

- No cycles => safe
- Knot => unsafe (multiple instances per resource problem)





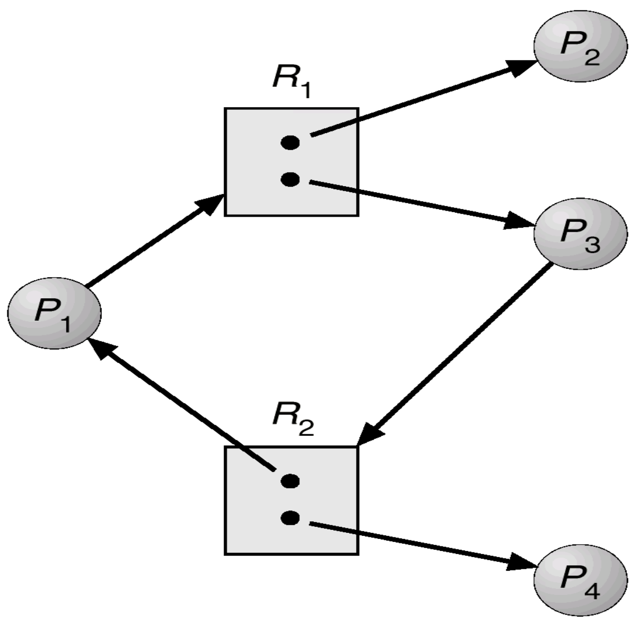
Deadlock Detection & Recovery

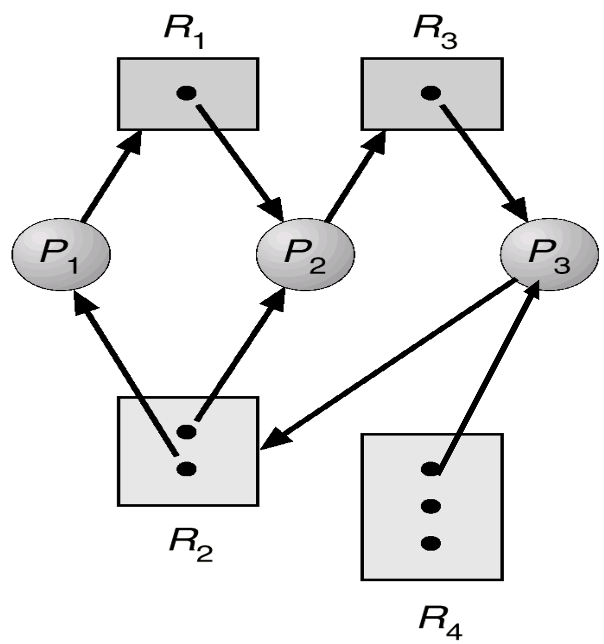
- Allow system to enter deadlock state
- Detection algorithm
  - Using resource-allocation graphs
  - Using Banker's algo idea
- Recovery scheme

Deadlock Detection using Graphs

an algorithm that searches for cycles (knots) in the resource-allocation graph:

- No cycles => no deadlock
- Knot => deadlock (multiple instances per resource problem)





Deadlock Detection without Graphs

Note:

- similar as detecting unsafe states using Banker's algo
- Q: how is similarity explained?
- Q: if they cost the same why not use avoidance instead of detection&recovery?

Data structures:

- *Available:* vector of length *m:* number of available resources of each type.
- *Allocation:* *n x m* matrix: number of resources of each type currently allocated to each process.
- *Request:* *n x m* matrix: **current request** of each process. *Request* [*ij*] = *k:* P_i is requesting *k* more instances of resource type R_j.

Detection Algorithm

1. Let *Work* and *Finish* be auxiliary vectors of length m and n, respectively. Initialize:
   (a) *Work* := *Available*
   (b) For i = 1,2, ..., n, if $Allocation_i \neq 0$, then *Finish*[i] := false; otherwise, *Finish*[i] := *true*.
2. Find 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 and P_i is deadlocked.

Example of Detection Algorithm

- Five processes P_0 through P_4; three resource types A (7 instances), *B* (2 instances), and *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 $\langle P_0, P_2, P_3, P_1, P_4\rangle$ will result in *Finish*[*i*] = true for all *i*.

Example (Cont.)

- P_2 requests an additional instance of type C.

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

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

- If algorithm is invoked arbitrarily, there may be many cycles in the resource graph $\Rightarrow$ we would not be able to tell which of the many deadlocked processes "caused" the deadlock.

Recovery from Deadlock: (1) Process Termination

- Abort all deadlocked processes.
- Abort one process at a time until deadlock is eliminated.
- In which order should we choose to abort? Criteria?
  - effect of the process' computation (breakpoints & rollback)
  - Priority of the process.
  - How long process has computed, and how much longer to completion.
  - Resources the process has used/needs to complete.
  - How many processes will need to be terminated.

Recovery from Deadlock: (2) Resource Preemption

- Select a victim
  - minimize cost.
- Rollback – return to some safe state, restart process from that state
  - Must do checkpointing for this to be possible.
- Watch for starvation – same process may always be picked as victim, include number of rollbacks in cost factor.

Combined Approach to Deadlock Handling

- Combine the three basic approaches (prevention, avoidance, detection), allowing the use of the optimal approach for each type of resources in the system:
  - Partition resources into hierarchically **ordered classes** (deadlocks may arise only within each class, then)
  - use most appropriate technique for handling deadlocks within each class, e.g:
    - internal (e.g. interactive I/O channels): *prevention by ordering*
    - process resources (e.g. files): *avoidance by knowing max needs*
    - main memory: *prevention by preemption*
    - swap space (blocks in disk, drum, ...): *prevention by preallocation*

RA & Deadlock Handling in Distributed Systems

- Note: no centralized control here!
  - Each site only knows about its own resources
  - Deadlock may involve distributed resources

Resource Allocation in Message-Passing Systems

Prevention (recall strategies: no cycles; request all resources at once; apply preemptive strategies) (apply in gen. din.phil)

- using *priorities/hierarchical ordering* of resources
  - Use resource-managers (1 proc/resource) and request resource from each manager (in the hierarchy order)
  - Use mutex (each fork is a mutex, execute Rikart&Agrawala for each)
- No hold&wait:
  - Each process is mutually exclusive with both its neighbours => each group of 3 neighbours is 1 Rikart&Agrawala "instance"
- **No Preemption** – If a process holding some resources requests another resource that cannot be immediately allocated, it releases the held resources and has to request them again (risk for starvation:cf PetersonStyer algo for avoiding starvation).

Distributed R.A. with Deadlock Avoidance or Deadlock Detection&Recovery

- Centralized control – one site is responsible for safety check or deadlock detection
  - Can be a bottleneck (in performance and fault-tolerance)
- Distributed control – all processes cooperate in the safety check or deadlock detection function
  - need of *consistent global state*
  - straightforward (expensive) approach: all processes try to learn global state
  - less expensive solutions tend to be complicated and/or unrealistic

- Distributed deadlock avoidance or detection&recovery is not very practical
  - Checking global states involves considerable processing overhead for a distributed system with a large number of processes and resources
  - Also: who will check if procs are all blocked?!