Operating Systems 412

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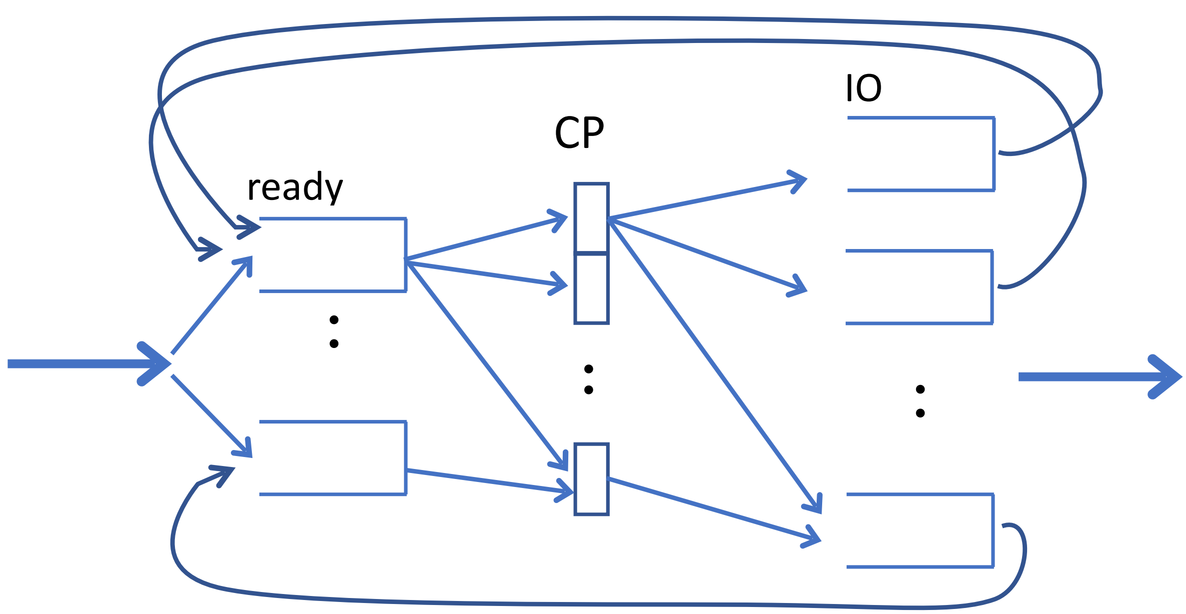
Queuing Theory without probabilities



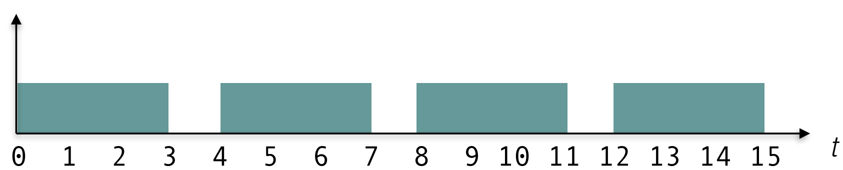
Queuing Theory without probabilities

- Queueing system
  - servers + waiting rooms
  - customers arrive, wait, get served, depart or go to next server
  - queueing disciplines
    - non-preemptive: fifo, priority, …
    - preemptive: round-robin, multi-level feedback, ...
- Operating systems are examples of queueing systems
  - servers: hw/sw resources (cpu, disk, req handler, …)
  - customers: PCBs, TCBs, ...
- Given: arrival rates, service times, queueing disciplines, ...
- Obtain: queue sizes, response times, fairness, bottlenecks, ...

Queuing Theory without probabilities

- Consider cars traveling on a road with a turn
  - each car takes 3 seconds to go through the turn
  - at most one car can be in the turn at any time
- N(t): # cars in the turn and waiting to enter the turn

arrival rate 1/4
load 3/4
uniform



arrival rate 1/4
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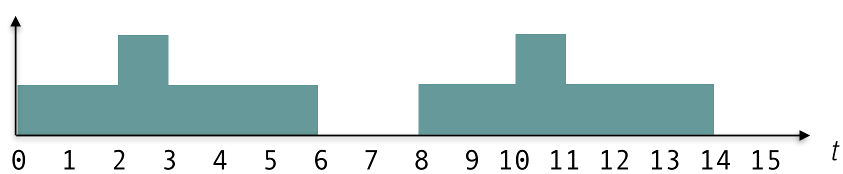


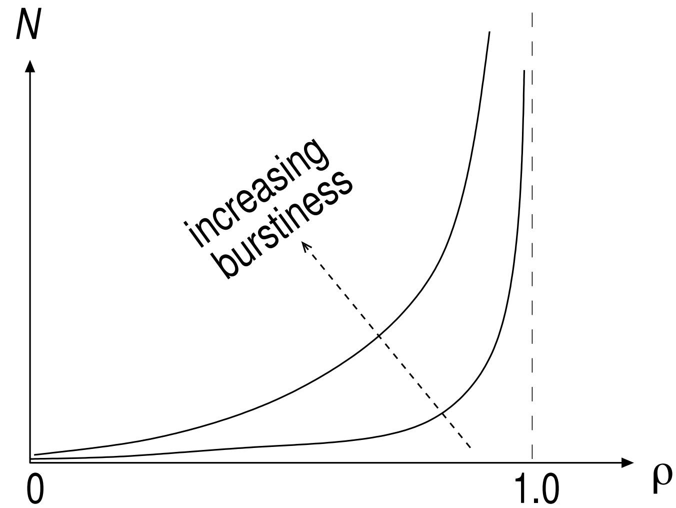
- Load < 1: *stable* w/ waits depending on burstiness
- Load > 1: *unstable*, ever-increasing waits

Queuing Theory without probabilities

- Assume unending stream of customers:
  - arrival rate λ or X: *# arrivals per second*
  - average service time S: *work needed per customer*
  - average response time R: *departure time D - arrival time A*
  - average wait time W: *response time - service time*
  - throughput X: *# departures per sec averaged over all time*
  - average customers in system N: *waiting or busy*
  - utilization U: *fraction of time server is busy*
- Typical goal
  - Given: arrival rate, avg service time, queueing discipline
  - Obtain: average response time, average queue size
- Little's Law (for any steady-state system):
  - $N = \lambda \times R$

Queuing Theory without probabilities

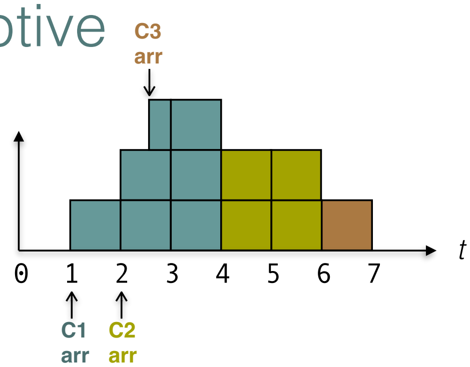
- Avg queue size N increases *exponentially* with load ρ
  - becoming ∞ as $\rho \to 1$
- N increases as burstiness increases



FCFS non-preemptive

customer	A_i	S_i	D_i	R_i	W_i
1	1.0	3.0	4.0	3.0	0.0
2	2.0	2.0	6.0	4.0	2.0
3	2.5	1.0	7.0	4.5	3.5

repeats every 10 seconds

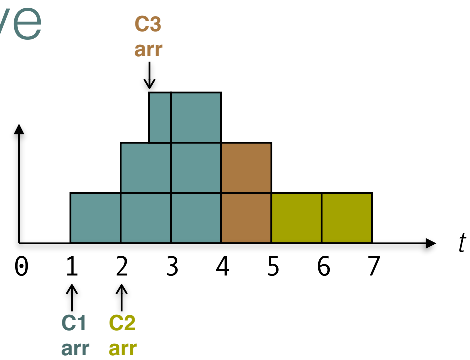


- System becomes empty at time 7 —> *stable*
  - Average response time: $R = \dfrac{3.0 + 4.0 + 4.0}{3} = \dfrac{11.5}{3}$ sec
  - Average wait time: $W = \dfrac{0.0 + 2.0 + 3.5}{3} = \dfrac{5.5}{3}$ sec
  - Arrival rate = throughput: $\lambda = \dfrac{3}{10}$ arrivals / sec
  - Utilization: $U = \dfrac{6}{10}$
  - Average number customers: $N = \lambda \times R = \dfrac{3}{10} \times \dfrac{11.5}{3} = \dfrac{11.5}{10}$

SJF non-preemptive

customer	A_i	S_i	D_i	R_i	W_i
1	1.0	3.0	4.0	3.0	0.0
2	2.0	2.0	7.0	5.0	3.0
3	2.5	1.0	5.0	2.5	1.5

repeats every 10 seconds

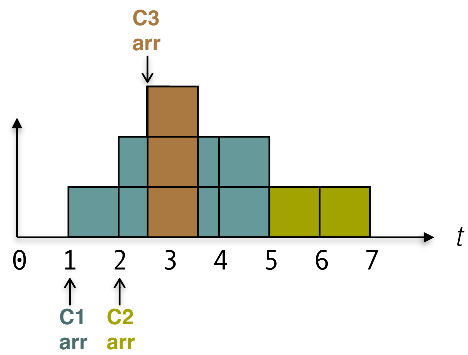


- System becomes empty at time 7 —> *stable*
  - Average response time: $R = \dfrac{3.0 + 5.0 + 2.5}{3} = \dfrac{10.5}{3}$ sec
  - Average wait time: $W = \dfrac{0.0 + 3.0 + 1.5}{3} = \dfrac{4.5}{3}$ sec
  - Arrival rate = throughput: $\lambda = \dfrac{3}{10}$ arrivals/sec
  - Utilization: $U = \dfrac{6}{10}$
  - Average number customers: $N = \lambda \times R = \dfrac{3}{10} \times \dfrac{10.5}{3} = \dfrac{10.5}{10}$

SJS preemptive

customer	A_i	S_i	D_i	R_i	W_i
1	1.0	3.0	5.0	4.0	1.0
2	2.0	2.0	7.0	5.0	3.0
3	2.5	1.0	3.5	1.0	0.0

repeats every 10 seconds

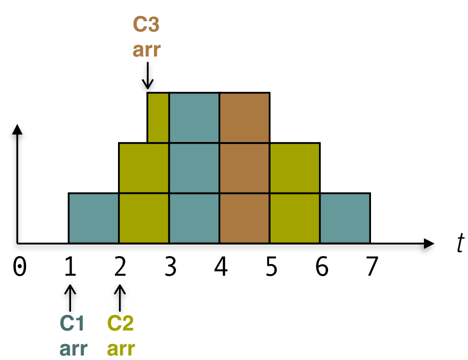


- System becomes empty at time 7 —> *stable*
  - Average response time: $R = \frac{4.0 + 5.0 + 1.0}{3} = \frac{10.0}{3}$ sec
  - Average wait time: $W = \frac{1.0 + 3.0 + 0.0}{3} = \frac{4.0}{3}$ sec
  - Arrival rate = throughput: $\lambda = \frac{3}{10}$ arrivals / sec
  - Utilization: $U = \frac{6}{10}$
  - Average number customers: $N = \lambda \times R = \frac{3}{10} \times \frac{10.0}{3} = \frac{10}{10}$

RR preemptive

customer	A_i	S_i	D_i	R_i	W_i
1	1.0	3.0	7.0	6.0	3.0
2	2.0	2.0	6.0	4.0	2.0
3	2.5	1.0	5.0	2.5	1.5

repeats every 10 seconds



- System becomes empty at time 7 —> *stable*
  - Average response time: $R = \frac{6.0 + 4.0 + 2.5}{3} = \frac{12.5}{3}$ sec
  - Average wait time: $W = \frac{3.0 + 2.0 + 1.5}{3} = \frac{6.5}{3}$ sec
  - Arrival rate = throughput: $\lambda = \frac{3}{10}$ arrivals / sec
  - Utilization: $U = \frac{6}{10}$
  - Average number customers: $N = \lambda \times R = \frac{3}{10} \times \frac{12.5}{3} = \frac{12.5}{10}$

Scheduling Summary

- response time vs average num customers:

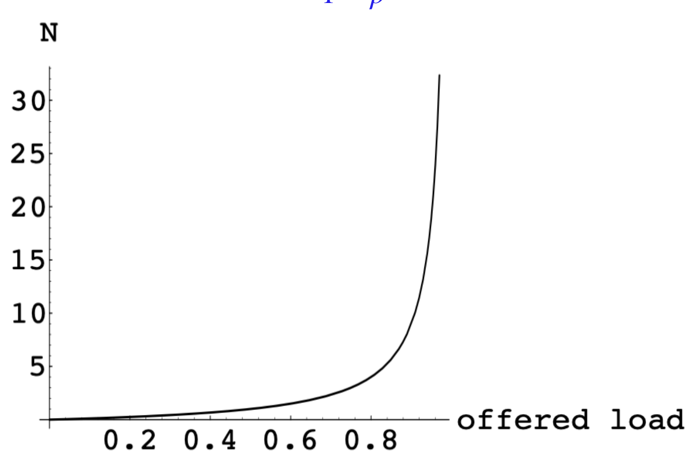
	FCFS	SJF	SJFP	RR
R	$\frac{11.5}{3}$	$\frac{10.5}{3}$	$\frac{10.0}{3}$	$\frac{12.5}{3}$
N	$\frac{11.5}{10}$	$\frac{10.5}{10}$	$\frac{10.0}{10}$	$\frac{12.5}{10}$

Little's Law:
$N = \lambda \times R$

- ratio of $R\,/\,N$ constant, because throughput (X) is same

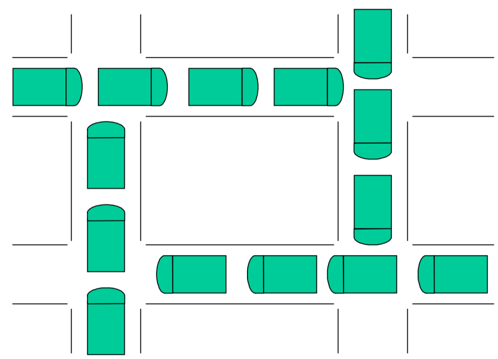
M/M/1 queues

- M/M/1 assumption
  - (M)emoryless (independent) interarrival times exp dist w/ mean $\frac{1}{\lambda}$
  - (M)emoryless (independent) service times exp dist w/ mean S
  - (1) server
- For stable M/M/1 queue: $N = \frac{\rho}{1-\rho}$



Deadlocks

- Necessary conditions for deadlock
  - Mutual exclusion - Threads claim exclusive control of resources
  - Hold and wait - Threads hold resources while waiting for additional resources
  - No preemption - Resources cannot be removed from threads that hold them
  - Circular wait - There exists a chain of threads such that each holds one or more resources that are requested by the next thread in the chain
- What to do?
  - prevent
  - avoid
  - deal with when they occur
  - pretend they never happen



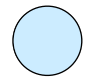
Resource Allocation Graph

A set of vertices *V* and a set of edges *E*:

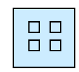
- V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set of all the processes in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set of all resource types in the system
- request edge: directed edge $P_i \rightarrow R_j$
- assignment edge: directed edge $R_j \rightarrow P_i$

Resource Allocation Graph (cont.)

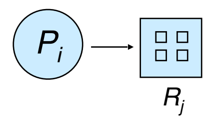
- Process



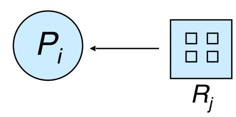
- Resource type with 4 instances



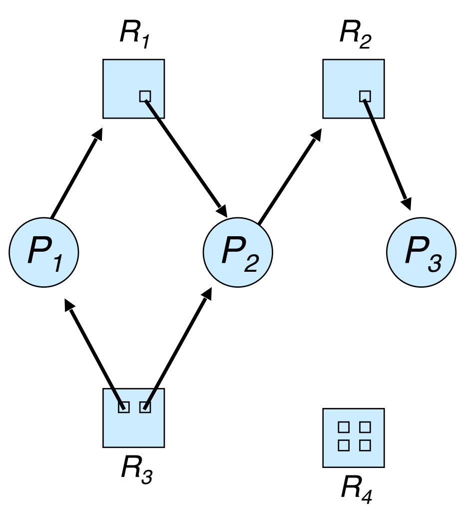
- P_i requests instance of R_j



- P_i is holding an instance of R_j

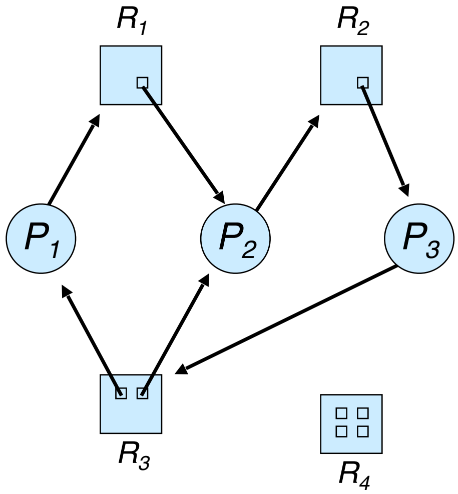


Resource Allocation Graph example



- P_1 requesting instance of R_1
- P_2 requesting instance of R_2
- one R_1 held by P_1
- one R_2 held by P_3
- distinct R_3 instances held by P_1 and P_2

Resource Allocation Graph deadlock



- $P_2 \rightarrow R_2 \rightarrow P_3 \rightarrow R_3 \rightarrow P_2$ deadlock
- $R_3 \rightarrow P_1 \rightarrow R_1 \rightarrow P_2$ not deadlock, but blocked by deadlock

Handling Deadlocks what to do

- What to do?
  - prevent
  - avoid
  - deal with when they occur
  - pretend they never happen

Deadlock Prevention

- Try to prevent one of the four conditions from holding true
  - Difficult to eliminate mutual exclusion
  - Prevent threads from requesting new resources when holding other resources (eliminates hold and wait)
  - Require threads not immediately able to get all needed resources to give up those they have (eliminates no preemption)
  - Require agreed-upon resource acquisition ordering (eliminates circular waiting).

Deadlock Prevention circular wait

- Agree on lexicographic ordering on lock acquisitions:

```
T1: pthread_mutex_lock(m1);   ①

    pthread_mutex_lock(m2);
```

```
T2: pthread_mutex_lock(m2);   ②

    pthread_mutex_lock(m1);
```

- or address-based:

```
if (m1 > m2) {          // grab in high-to-low address order
    pthread_mutex_lock(m1);
    pthread_mutex_lock(m2);
} else {
    pthread_mutex_lock(m2);
    pthread_mutex_lock(m1);
}
```

Deadlock Prevention circular wait

- Agree on lexicographic ordering on lock acquisitions:

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T1: pthread_mutex_lock(m1);      ①
    pthread_mutex_lock(m2);
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}
```


Deadlock Prevention circular wait

- Agree on lexicographic ordering on lock acquisitions:

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T1: pthread_mutex_lock(m1);      ①
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- or address-based:

```
if (m1 > m2) {          // grab in high-to-low address order
    pthread_mutex_lock(m1);
    pthread_mutex_lock(m2);
} else {
    pthread_mutex_lock(m2);
    pthread_mutex_lock(m1);
}
```

Deadlock Prevention hold and wait

- Acquire all locks at once:

```
pthread_mutex_lock(prevention);          // begin acquisition
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
...
pthread_mutex_unlock(prevention);        // end
```

- But:
  - `prevention` lock is global
  - need complete information

Deadlock Prevention no preemption

- *Try* locks
  - atomically grab lock if available, or return w/ error

```
top:
    pthread_mutex_lock(L1);              // begin acquisition
    if (pthread_mutex_trylock(L2) != 0) {
        pthread_mutex_unlock(L1);
        goto top;
    }
```

- Works even if other thread choose different order. However: *livelock:*
  - Possible, though unlikely, that the threads both repeatedly back off. We could fix this with random delays.
  - Other issue is *encapsulation*: some of the locks might be acquired in called functions, making jump back to initial state more difficult

Deadlock Prevention mutual exclusion

- *Lock-free* and *wait-free* data structures and algorithms
  - use atomic instructions such as *CompareAndSwap*

// pseudocode of atomic assembly instruction

```
int CompareAndSwap(int *address, int expected, int new) {
    if (*address == expected) {
        *address = new;
        return 1;                          // success
    }
    return 0;                              // failure
}
```

- Use with the following:

```
void AtomicIncrement(int *value, int amount) {
    do {
        int old = *value;
    } while (CompareAndSwap(value, old, old + amount) == 0);
}
```

Deadlock Prevention more wait-free

// mutex-based

```
void insert(int value) {
    node_t *n = malloc(sizeof(node_t));
    n->value = value;
    pthread_mutex_lock(listlock);   // begin critical section
    n->next  = head;
    head     = n;
    pthread_mutex_unlock(listlock); // end critical section
}
```

// fixed

```
void insert(int value) {
    node_t *n = malloc(sizeof(node_t)); assert(n != NULL);
    n->value = value;
    do{
        n->next = head;
    } while (CompareAndSwap(&head, n->next, n) == 0);
}
```

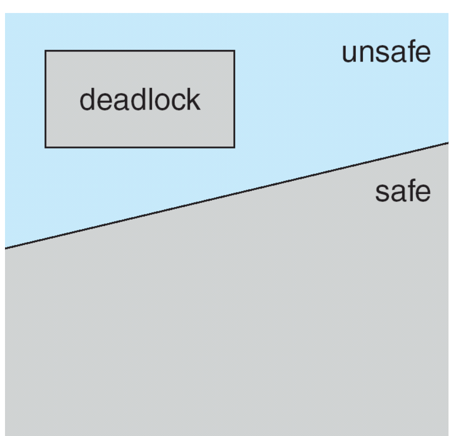
Deadlock Avoidance safe states

When a process requests an available resource, system must decide if immediate allocation leaves the system in a safe state.

- System is in *safe state* if there exists:
  - sequence <P_1, P_2, …, P_n> of ALL the processes in the systems such that for each P_i, the resources that P_i can still request can be satisfied by currently available resources + resources held by all P_j s.t. $j < i$
- That is:
  - If P_i's resource needs are not immediately available, then P_i can wait until all P_j have finished
  - When P_j is finished, P_i can obtain needed resources, execute, return allocated resources, and terminate
  - When P_i terminates, P_{i+1} can obtain its needed resources, …

Deadlock Avoidance safe states

- In other words:
  - System is in safe state ⟶ no deadlocks
  - System is in unsafe state ⟶ possibility of deadlocks
- Avoidance of unsafe states ensure no deadlocks.



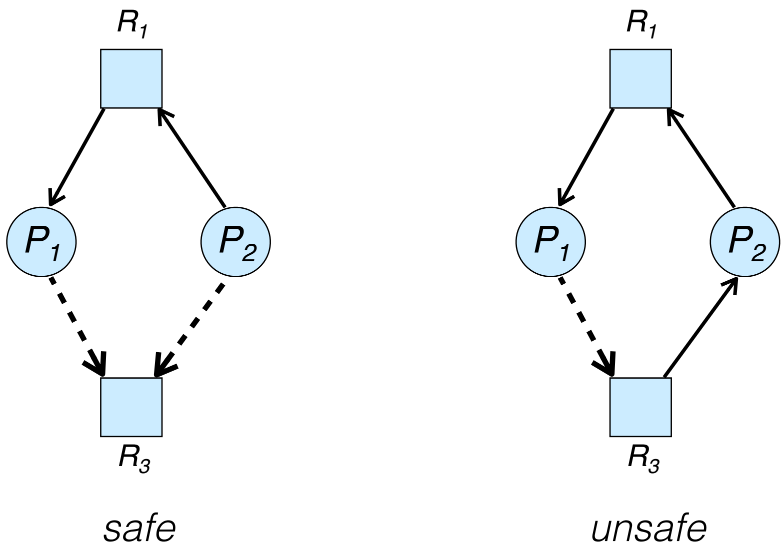
Deadlock Avoidance safe states

- Single instance of a resource type
  - Use a resource-allocation graph
- Multiple instances of resource types
  - Use the banker's algorithm

Deadlock Avoidance safe states

- New claim edge $P_i \rightarrow R_j$ indicates P_i may request resource R_J. (represented by dashed line)
- Claim edge converts to request edge when a process requests a resource
- Request edge converted to an assignment edge when the resource is allocated to the process
- When a resource is released by a process, assignment edge reconverts to a claim edge
- Resources must be claimed a priori in the system.

Deadlock Avoidance safe states

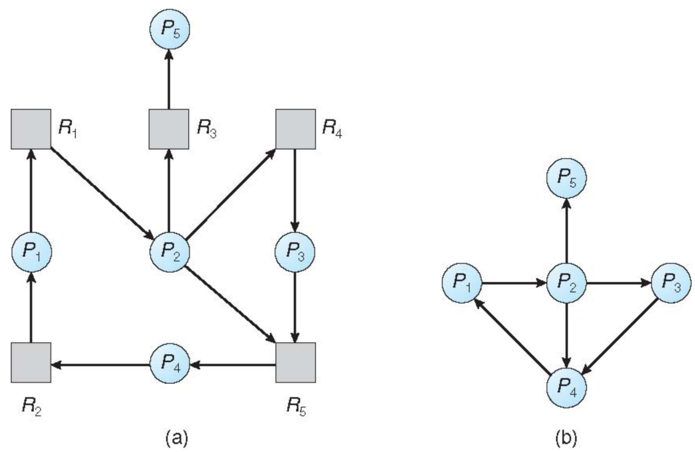


A request by P_i for resource R_j can be granted only if converting the request edge to an assignment edge does not result in the formation of a cycle in the resource allocation graph

Deadlock Mitigation dealing with it

- Maintain wait-for graph
  - Nodes are processes
  - $P_i \rightarrow P_j$ if P_i is waiting for resource held by P_j
- Periodically invoke an algorithm that searches for a cycle in the graph. If there is a cycle, there exists a deadlock
- An algorithm to detect a cycle in a graph requires an order of n^2 operations, where n is the number of vertices in the graph

Deadlock Mitigation dealing with it



Resource-Allocation Graph Corresponding wait-for graph

- Construct the waits for graph
- Check for cycles
- Pick *any* thread of the cycle and kill it

Deadlock Mitigation ignoring it

"Not everything worth doing is worth doing well" - Tom West

- Consequence may be
  - minor
  - very rare