Deadlocks

Deadlock

- A set of processes is deadlocked, when each process in the set is blocked awaiting an event that can only be triggered by another blocked process in the set.
  - Typically involves processes competing for the same set of resources
- No efficient solution

Deadlocks

- **Deadlock:** A condition where two or more threads are waiting for an event that can only be generated by these same threads.
- Example:

Process A:

```
printer.Wait();
disk.Wait();

// copy from disk
// to printer

printer.Signal();
disk.Signal();
```

Process B:

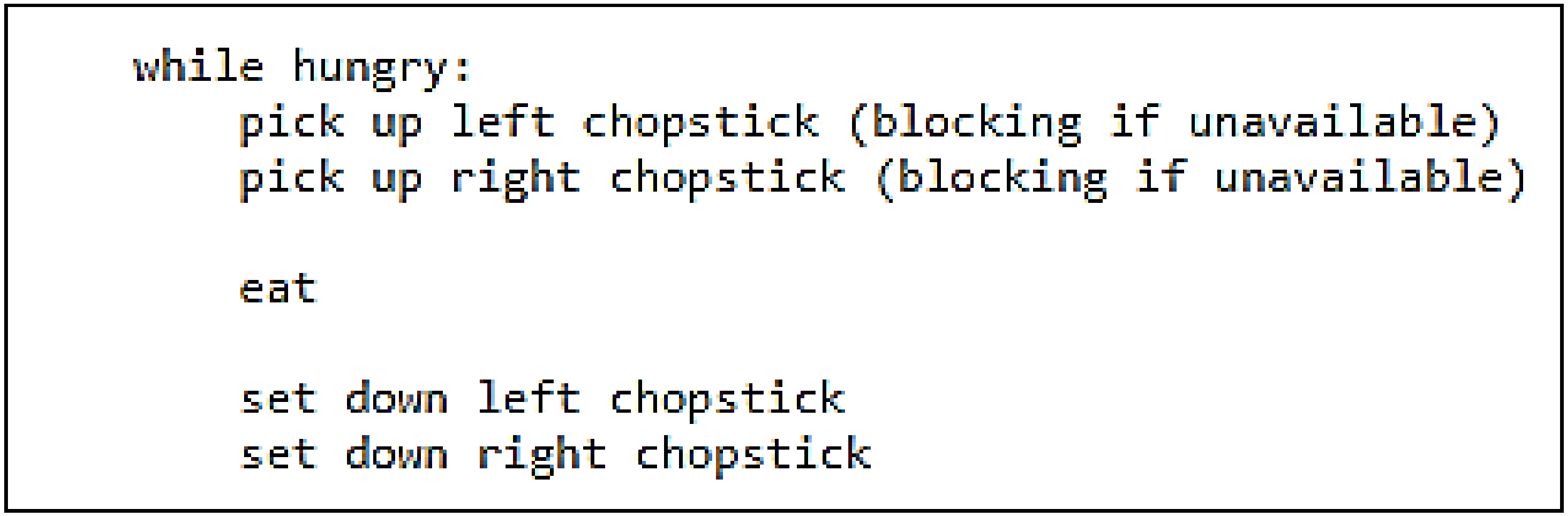
```
disk.Wait();
printer.Wait();

// copy from disk
// to printer

printer.Signal();
disk.Signal();
```

Consider the "dining philosophers" problem: n philosophers are sitting around a table, wanting to eat. Between each pair of philosophers is a single chopstick; a philosopher needs two chopsticks to eat. One possible way to write the pseudocode for each philosopher:

Dining philosophers first try



```
while hungry:
    pick up left chopstick (blocking if unavailable)
    pick up right chopstick (blocking if unavailable)

    eat

    set down left chopstick
    set down right chopstick
```

This solution may exhibit deadlock if all threads pick up their left chopstick before any thread picks up the right chopstick. At that point, all of the philosophers are waiting for a chopstick, but no chopstick is available, so the system is deadlocked.

Deadlocks: Terminology

- **Deadlock** can occur when several threads compete for a finite number of resources simultaneously
- **Deadlock detection** finds instances of deadlock when threads stop making progress and tries to recover
- **Deadlock prevention** imposes restrictions on programs to prevent the possibility of deadlock
- **Deadlock avoidance** algorithms check resource requests and availability at runtime to avoid deadlock
- **Starvation** occurs when a thread waits indefinitely for some resource, but other threads are actually using it (making progress).

  => Starvation is a different condition from deadlock

Deadlock vs Livelock

- A **deadlock** is a state in which each member of a group of actions, is waiting for some other member to release a lock

- A **livelock** is similar to a deadlock, except that the states of the processes involved in the livelock constantly change with regard to one another, none progressing.
  - For example, consider two processes each waiting for a resource the other has but waiting in a non-blocking manner.
  - When each learns they cannot continue they release their held resource and sleep for 30 seconds, then they retrieve their original resource followed by trying to the resource the other process held, they left, then reacquired.
  - Since both processes are trying to cope (just badly), this is a livelock.

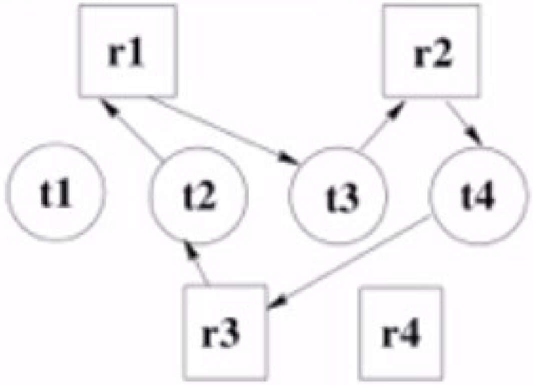
Necessary Conditions for Deadlock

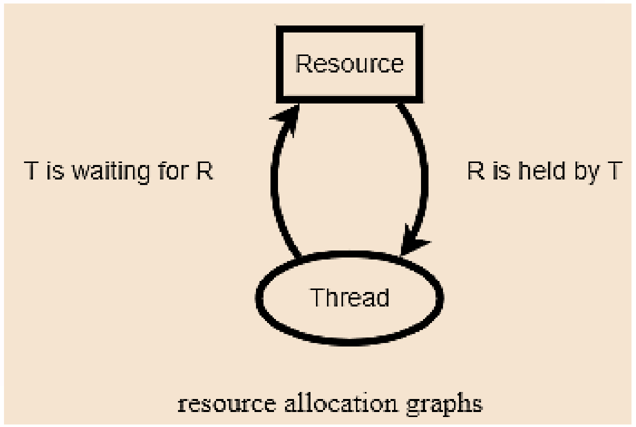
Deadlock can happen if **all** the following conditions hold.

- **Mutual Exclusion:** at least one thread must hold a resource in non-sharable mode, i.e., the resource may only be used by one thread at a time.
- **Hold and Wait:** at least one thread holds a resource and is waiting for other resource(s) to become available. A different thread holds the resource(s).
- **No Preemption:** A thread can only release a resource voluntarily; another thread or the OS cannot force the thread to release the resource.
- **Circular wait:** A set of waiting threads $\{t_1, ..., t_n\}$ where t_i is waiting on t_{i+1} ($i = 1$ to n) and t_n is waiting on t_1.

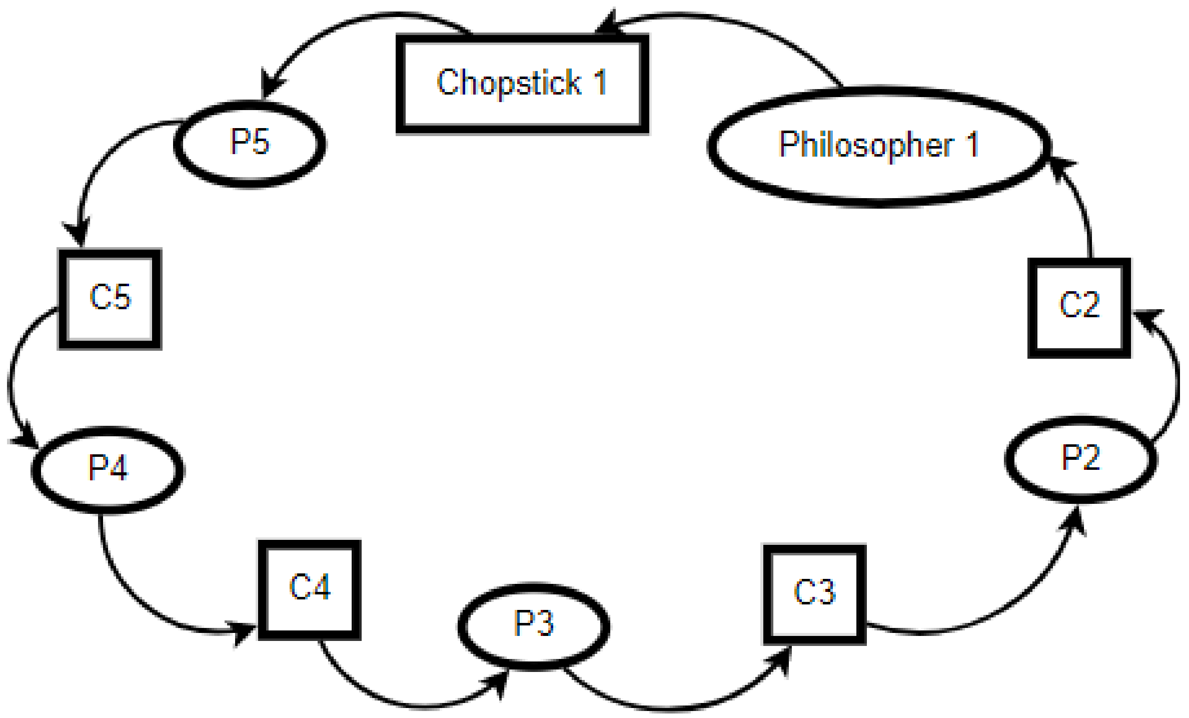
Deadlock Detection Using a Resource Allocation Graph

- We define a graph with vertices that represent both resources $\{r_1, ..., r_m\}$ and threads $\{t_1, ..., t_n\}$.
  - A directed edge from a thread to a resource, $t_i \rightarrow r_j$ indicates that t_i has requested that resource, but has not yet acquired it (*Request Edge*)
  - A directed edge from a resource to a thread $r_j \rightarrow t_i$ indicates that the OS has allocated r_j to t_i (*Assignment Edge*)
- If the graph has no cycles, no deadlock exists.
- If the graph has a cycle, deadlock might exist.





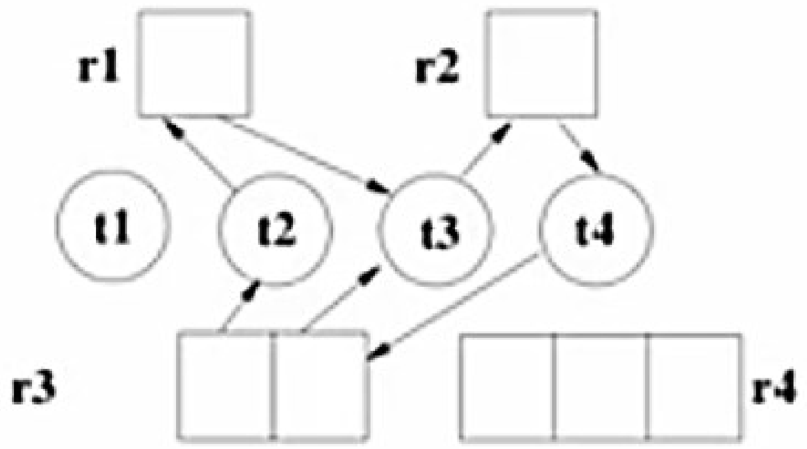
Assuming mutual exclusion, no preemption, and hold and wait, the system is deadlocked if and only if there is a (directed) cycle in the resource allocation graph. Here is the graph for the deadlocked dining philosophers scenario described above:

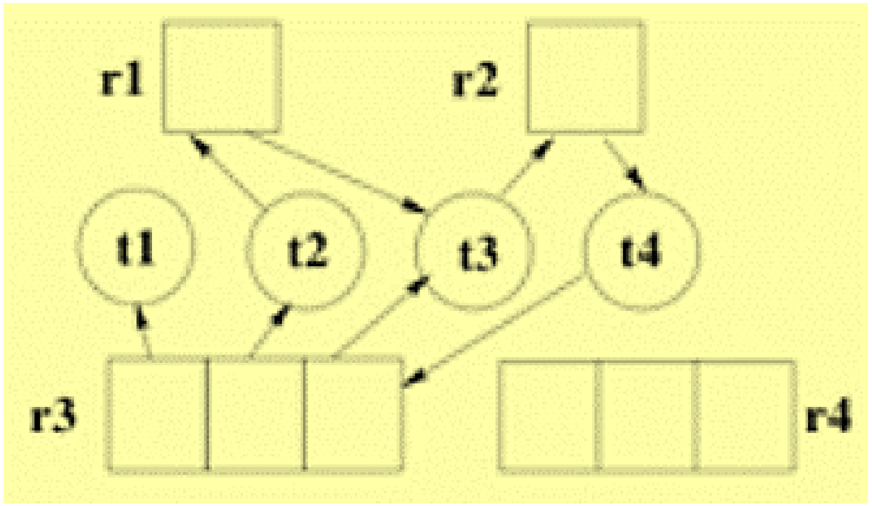


dining philosophers deadlock

Deadlock Detection Using a Resource Allocation Graph

- What if there are multiple interchangeable instances of a resource?
  - Then a cycle indicates only that deadlock *might* exist.
  - If any instance of a resource involved in the cycle is held by a thread not in the cycle, then we can make progress when that resource is released.





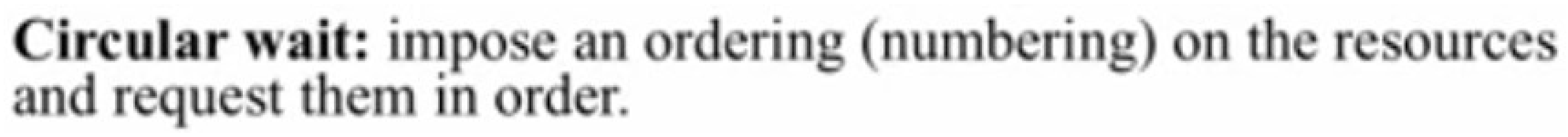
Detect Deadlock and Then Correct It

- Scan the resource allocation graph for cycles, and then break the cycles.
- Different ways of breaking a cycle:
  - Kill all threads in the cycle.
  - Kill the threads one at a time, forcing them to give up resources.
  - Preempt resources one at a time rolling back the state of the thread holding the resource to the state it was in prior to getting the resource. This technique is common in database transactions.
- Detecting cycles takes $O(n^2)$ time, where n is $|T| + |R|$. When should we execute this algorithm?
  - Just before granting a resource, check if granting it would lead to a cycle? (Each request is then $O(n^2)$.)
  - Whenever a resource request can't be filled? (Each failed request is $O(n^2)$.)
  - On a regular schedule (hourly or ...)? (May take a long time to detect deadlock)
  - When CPU utilization drops below some threshold? (May take a long time to detect deadlock)
- What do current OS do?
  - Leave it to the programmer/application.

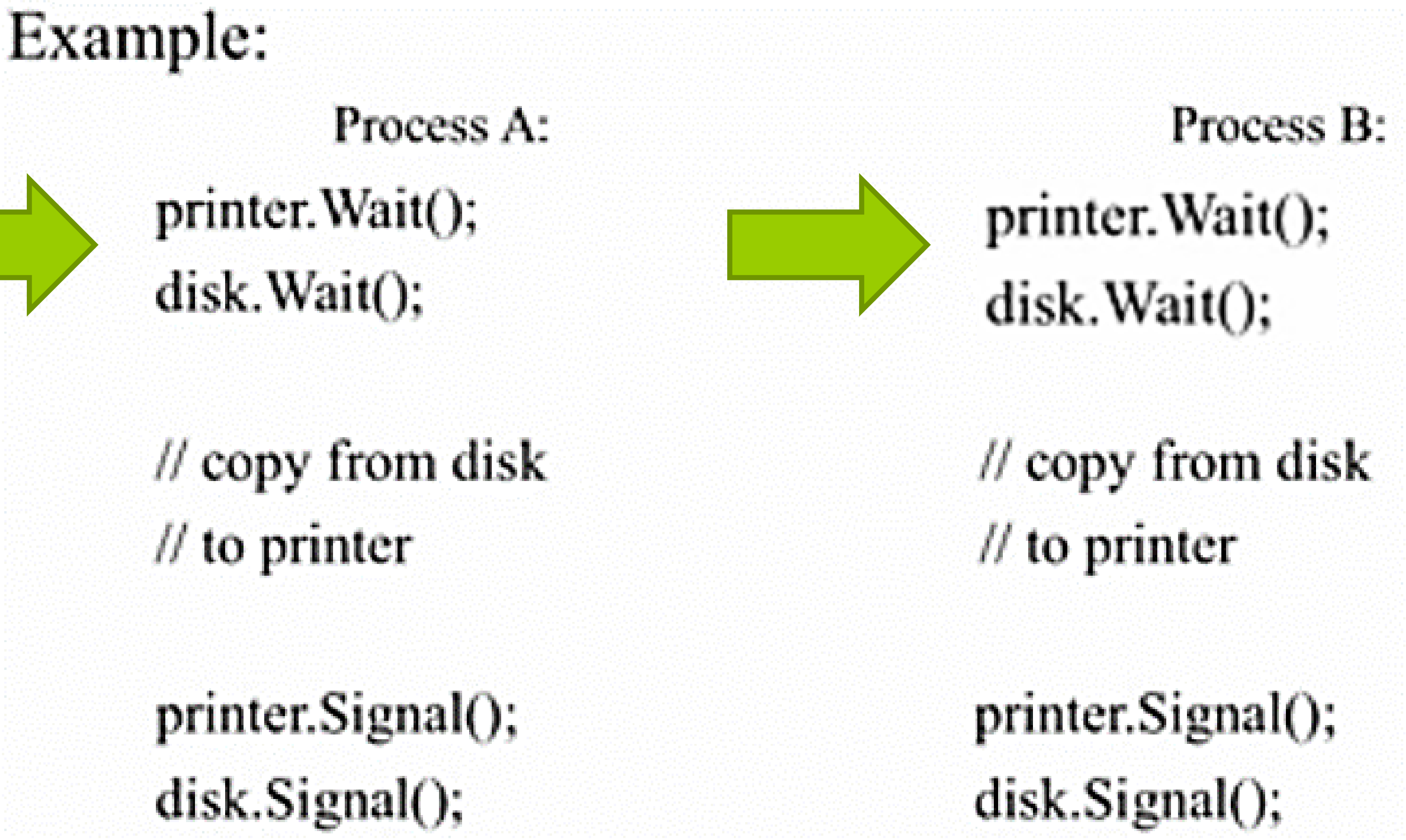
Deadlock Prevention

Prevent deadlock: ensure that at least one of the necessary conditions doesn't hold.

1. **Mutual Exclusion:** make resources sharable (but not all resources can be shared)
2. **Hold and Wait:**
   - Guarantee that a thread cannot hold one resource when it requests another
   - Make threads request all the resources they need at once and make the thread release all resources before requesting a new set.
3. **No Preemption:**
   - If a thread requests a resource that cannot be immediately allocated to it, then the OS preempts (releases) all the resources that the thread is currently holding.
   - Only when all of the resources are available, will the OS restart the thread.
   - *Problem:* not all resources can be easily preempted, like printers.
4. **Circular wait:** impose an ordering (numbering) on the resources and request them in order.



Circular wait: impose an ordering (numbering) on the resources and request them in order.



Example:

```
        Process A:                          Process B:

    printer.Wait();                     printer.Wait();
    disk.Wait();                        disk.Wait();

    // copy from disk                   // copy from disk
    // to printer                       // to printer

    printer.Signal();                   printer.Signal();
    disk.Signal();                      disk.Signal();
```

Deadlock Avoidance with Resource Reservation

- Threads provide advance information about the maximum resources they may need during execution
- Define a sequence of threads $\{t_1, ..., t_n\}$ as *safe* if for each t_i, the resources that t_i can still request can be satisfied by the currently available resources plus the resources held by all t_j, $j < i$.
- A *safe state* is a state in which there is a safe sequence for the threads.
- An unsafe state is not equivalent to deadlock, it just may lead to deadlock, since some threads might not actually use the maximum resources they have declared.
- Grant a resource to a thread is the new state is safe
- If the new state is unsafe, the thread must wait even if the resource is currently available.
- This algorithm ensures no circular-wait condition exists.

Example

- Threads t_1, t_2, and t_3 are competing for 12 tape drives.
- Currently, 11 drives are allocated to the threads, leaving 1 available.
- The current state is *safe* (there exists a safe sequence, $\{t_1, t_2, t_3\}$ where all threads may obtain their maximum number of resources without waiting)
  - t_1 can complete with the current resource allocation
  - t_2 can complete with its current resources, plus all of t_1's resources, and the unallocated tape drive.
- t_3 can complete with all its current resources, all of t_1 and t_2's resources, and the unallocated tape drive.

	max need	in use	could want
t_1	4	3	1
t_2	8	4	4
t_3	12	4	8

Example (contd)

- If t_3 requests one more drive, then it must wait because allocating the drive would lead to an unsafe state.
- There are now 0 available drives, but each thread might need at least one more drive.

	max need	in use	could want
t_1	4	[redacted]	1
t_2	8	[redacted]	4
t_3	12	[redacted]	7

Banker's Algorithm

- This algorithm handles multiple instances of the same resource.
- Force threads to provide advance information about what resources they may need for the duration of the execution.
- The resources requested may not exceed the total available in the system.
- The algorithm allocates resources to a requesting thread if the allocation leaves the system in a safe state.
- Otherwise, the thread must wait.

Avoiding Deadlock with Banker's Algorithm

```
class ResourceManager {
  int n;        // # threads
  int m;      // # resources
  int avail[m], // # of available resources of each type
  max[n,m],   // # of each resource that each thread may want
  alloc[n,m], //# of each resource that each thread is using
  need[n,m],   // # of resources that each thread might still
   request
```

Banker's Algorithm:Resource Allocation

```
public void synchronized allocate (int request[m], int i) {
  // request  contains the resources being requested
  // i is the thread making the request

  if (request > need[i])  //vector comparison
    error();  // Can't request more than you declared
  else while (request[i] > avail)
    wait();   // Insufficient resources available

  // enough resources exist to satisfy the requests
  // See if the request would lead to an unsafe state
  avail = avail - request;  // vector additions
  alloc[i] = alloc[i] + request;
  need[i] = need[i] - request;

  while ( !safeState () ) {
    // if this is an unsafe state, undo the allocation and wait
    <undo the changes to avail, alloc[i], and need[i]>
    wait ();
    <redo the changes to avail, alloc[i], and need[i]>
} }
```

Banker's Algorithm: Safety Check

```
private boolean safeState () {
  boolean work[m] = avail[m]; // accommodate all resources
  boolean finish[n] = false;  // none finished yet

  // find a process that can complete its work now
  while (find i such that finish[i] == false and need[i] <= work) { // vector operations
    work = work + alloc[i]
    finish[i] = true;
  }

  if (finish[i] == true for all i)
    return true;
  else
    return false;
}
```

- Worst case: requires O(mn^2) operations to determine if the system is safe.

Example using Banker's Algorithm

System snapshot:

	Max	Allocation	Available
	A B C	A B C	A B C
P_0	0 0 1	0 0 1	
P_1	1 7 5	1 0 0	
P_2	2 3 5	1 3 5	
P_3	0 6 5	0 6 3	
Total		2 9 9	1 5 2

Example (contd)

- How many resources are there of type (A,B,C)?

  resources = total + avail: (3,14,11)

- What is the contents of the Need matrix?

  Need = Max - Allocation

	A B C
P_0	0 0 0
P_1	0 7 5
P_2	1 0 0
P_3	0 0 2

	Max	Allocation	Available
	A B C	A B C	A B C
P_0	0 0 1	0 0 1	
P_1	1 7 5	1 0 0	
P_2	2 3 5	1 3 5	
P_3	0 6 5	0 6 3	
Total		2 9 9	1 5 2

- Is the system in a safe state? Why?
  - Yes, because the processes can be executed in the sequence P_0, P_2, P_1, P_3, even if each process asks for its maximum number of resources when it executes.

Example (contd)

- If a request from process P_1 arrives for additional resources of (0,5,2), can the Banker's algorithm grant the request immediately?
- What would be the new system state after the allocation?

	Max	Allocation	Available
	A B C	A B C	A B C
P_0	0 0 1	0 0 1	
P_1	1 7 5	1 0 0	
P_2	2 3 5	1 3 5	
P_3	0 6 5	0 6 3	
Total		2 9 9	1 5 2

- What is a sequence of process execution that satisfies the safety constraint?

Example: solutions

- If a request from process P_1 arrives for additional resources of (0,5,2), can the Banker's algorithm grant the request immediately? Show the system state, and other criteria.

  Yes. Since

  1. $(0,5,2) \leq (1,5,2)$, the Available resources, and
  2. $(0,5,2) + (1,0,0) = (1,5,2) \leq (1,7,5)$, the maximum number P_1 can request.
  3. The new system state after the allocation is:

	Max	Allocation	Available
	A B C	A B C	A B C
P_0	0 0 1	0 0 1	
P_1	1 7 5	**1 5 2**	
P_2	2 3 5	1 3 5	
P_3	0 6 5	0 6 3	
		2 14 11	**1 0 0**

and the sequence P_0, P_2, P_1, P_3 satisfies the safety constraint.