# Deadlocks
# Detection and Avoidance

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# System Model

- There are non-shared computer resources
  - Maybe more than one instance
  - Printers, Semaphores, Tape drives, CPU
- Processes need access to these resources
  - Acquire resource
    - If resource is available, access is granted
    - If not available, the process is blocked
  - Use resource
  - Release resource
- Undesirable scenario:
  - Process A acquires resource 1, and is waiting for resource 2
  - Process B acquires resource 2, and is waiting for resource 1

  $\Rightarrow$ Deadlock!

# Example 1: Semaphores

```
semaphore: mutex1 = 1    /* protects resource 1 */
           mutex2 = 1    /* protects resource 2 */
```

Process A code:

```
{
    /* initial compute */
   P(file)
   P(printer)

  /* use both resources */

   V(printer)
   V(file)
}
```

Process B code:

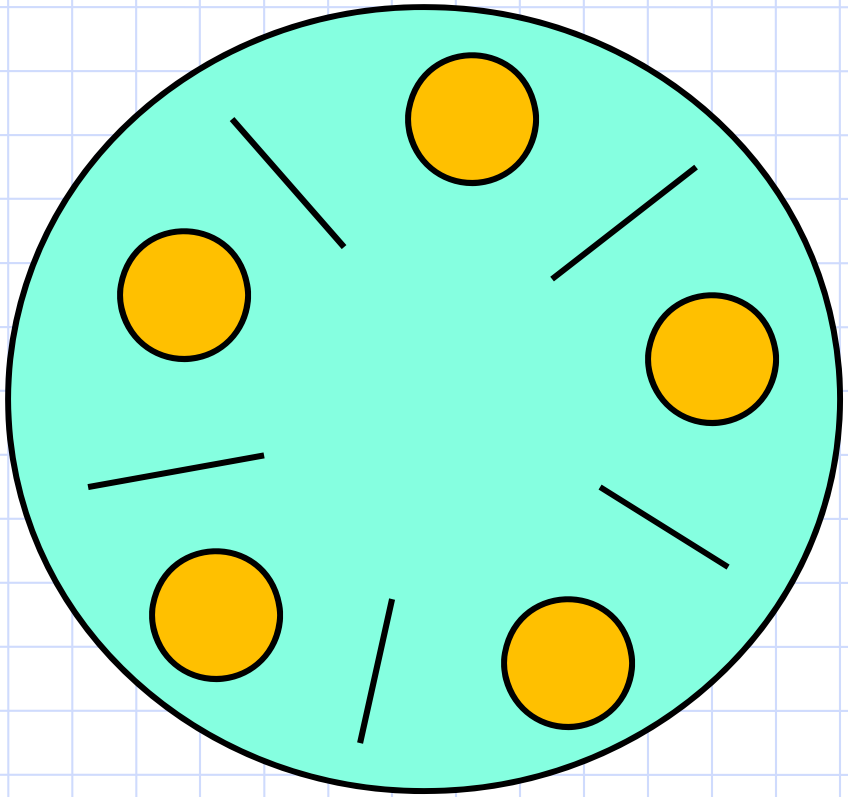
```
{
    /* initial compute */
   P(printer)
   P(file)

  /* use both resources */

   V(file)
   V(printer)
}
```

# Simplest deadlock

# Example 2: Dining Philosophers

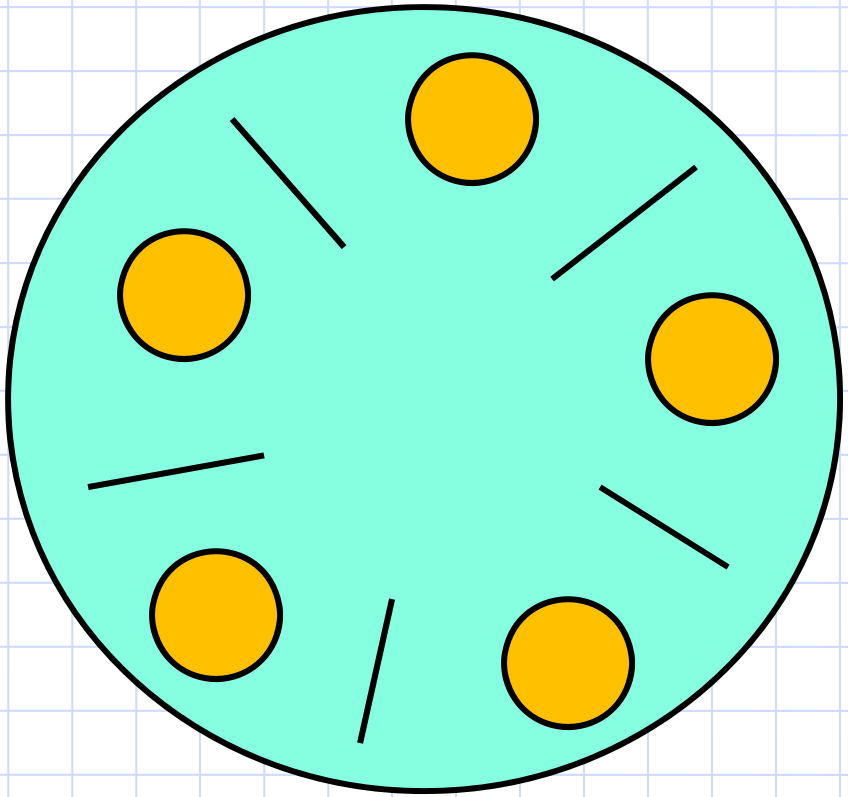


```
class Philosopher:
chopsticks[N] = [Semaphore(1),…]
Def __init__(mynum)
  self.id = mynum
Def eat():
   right = (self.id+1) % N
   left = (self.id-1+N) % N
   while True:


      # om nom nom
```

- Philosophers go out for Chinese food
- They need exclusive access to two chopsticks to eat their food

# Example 2: Dining Philosophers



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Def __init__(mynum)
  self.id = mynum
Def eat():
   right = (self.id+1) % N
   left = (self.id-1+N) % N
   while True:
      P(left)
      P(right)
      # om nom nom
      V(right)
      V(left)
```

- Philosophers go out for Chinese food
- They need exclusive access to two chopsticks to eat their food

# More Complicated Deadlock

# Deadlocks

Deadlock exists among a set of processes if

- Every process is waiting for an event
- This event can be caused only by another process in the set that in turn is waiting for an event

- Typically, the event is the acquire or release of another resource

- Kansas 20th century law: “When two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone”

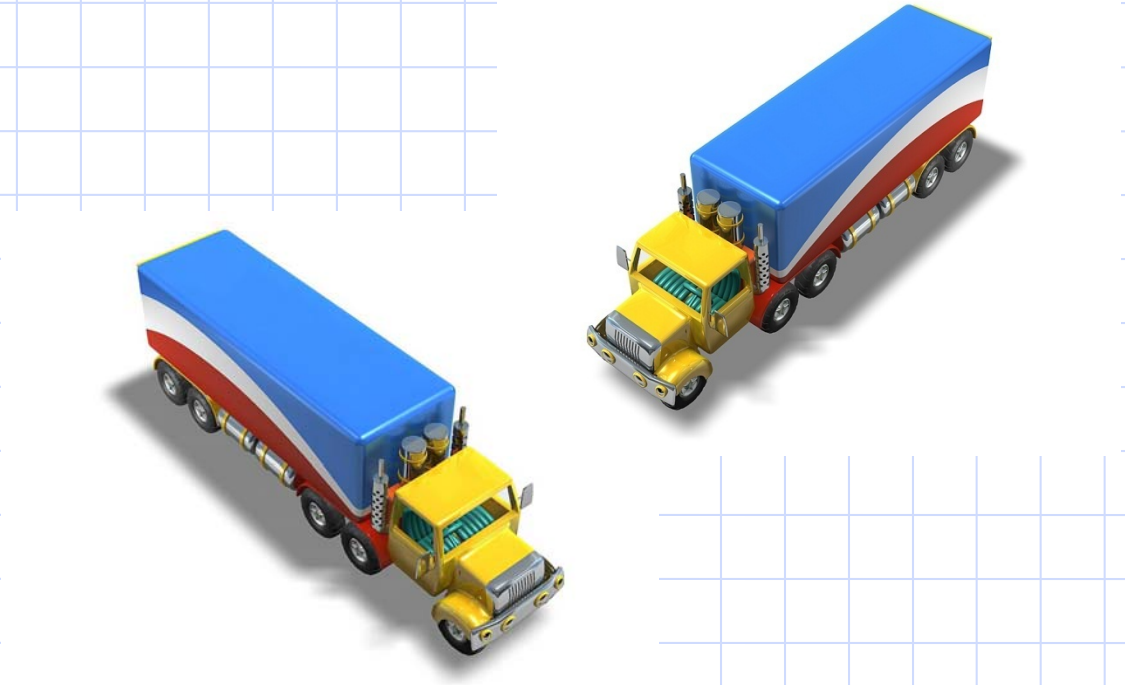
# Four Conditions for Deadlock

- Necessary conditions for deadlock to exist:
  - **Mutual Exclusion**
    - At least one resource must be held in non-sharable mode
  - **Hold and wait**
    - There exists a process holding a resource, and waiting for another
  - **No preemption**
    - Resources cannot be preempted
  - **Circular wait**
    - There exists a set of processes $\{P_1, P_2, \ldots P_N\}$, such that
      - $P_1$ is waiting for $P_2$, $P_2$ for $P_3$, .... and $P_N$ for $P_1$

***All*** four conditions must hold for deadlock to occur

# Real World Deadlocks?

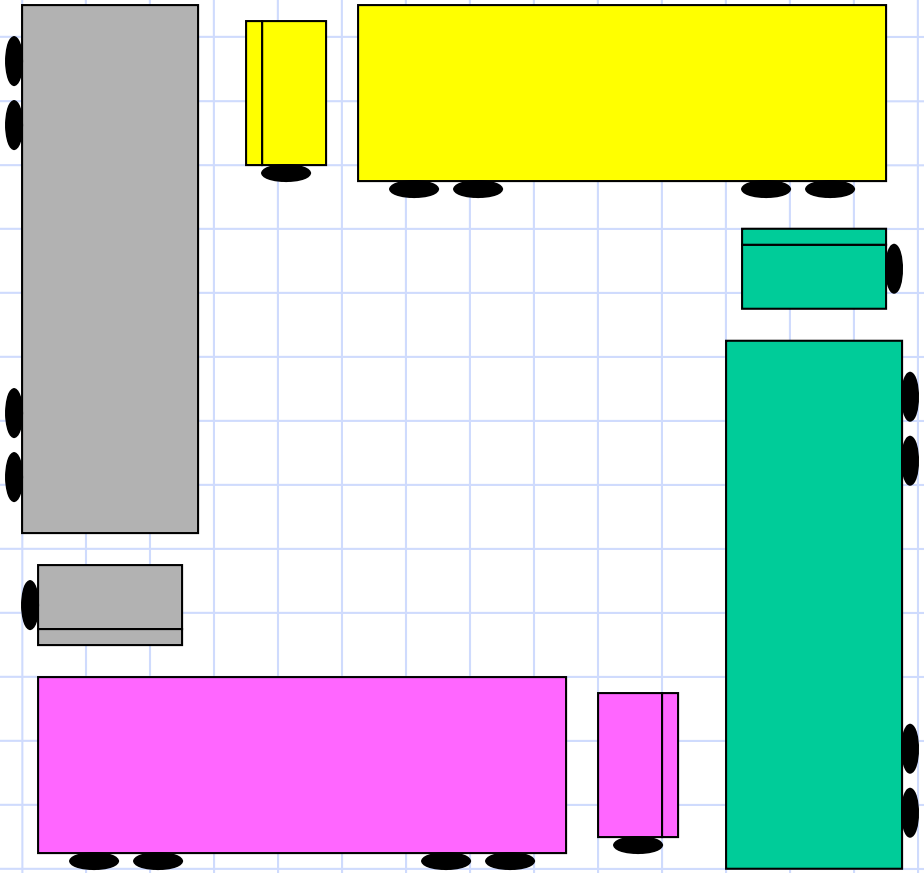
- Truck A has to wait for truck B to move



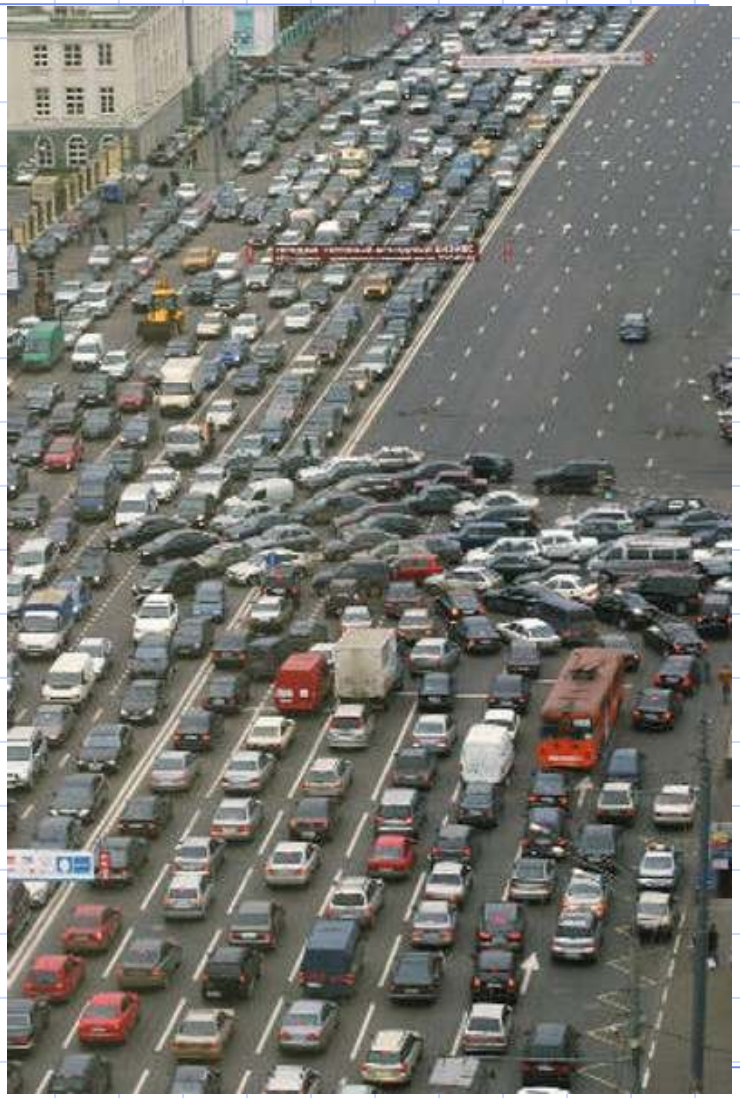
- Not deadlocked

# Real World Deadlocks?

- Gridlock

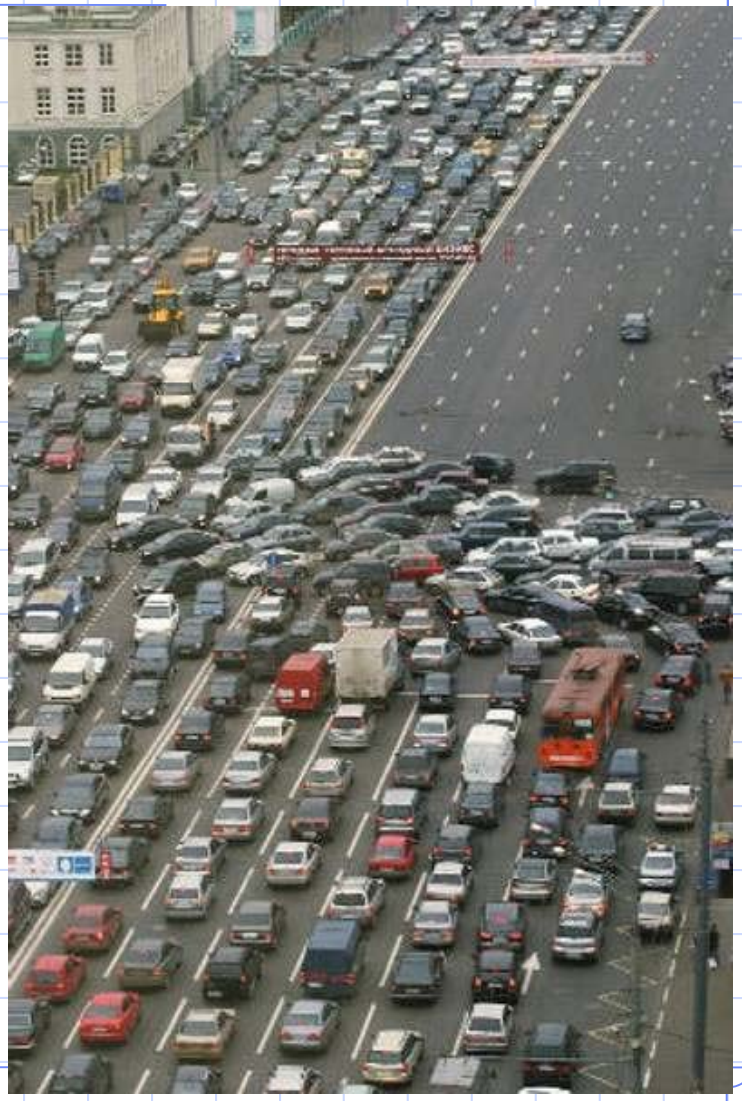


# Deadlock in Real Life?



# Deadlock in Real Life?

- No circular wait!
- Not a deadlock!
  - At least, not as far as we can see from the picture
- Will ultimately resolve itself given enough time



# Deadlock in Real Life

# Avoiding deadlock

- How do cars do it?
  - Try not to block an intersection
  - Must back up if you find yourself doing so
- Why does this work?
  - “Breaks” a wait-for relationship
  - Intransigent waiting (refusing to release a resource) is one of the four key elements of a deadlock

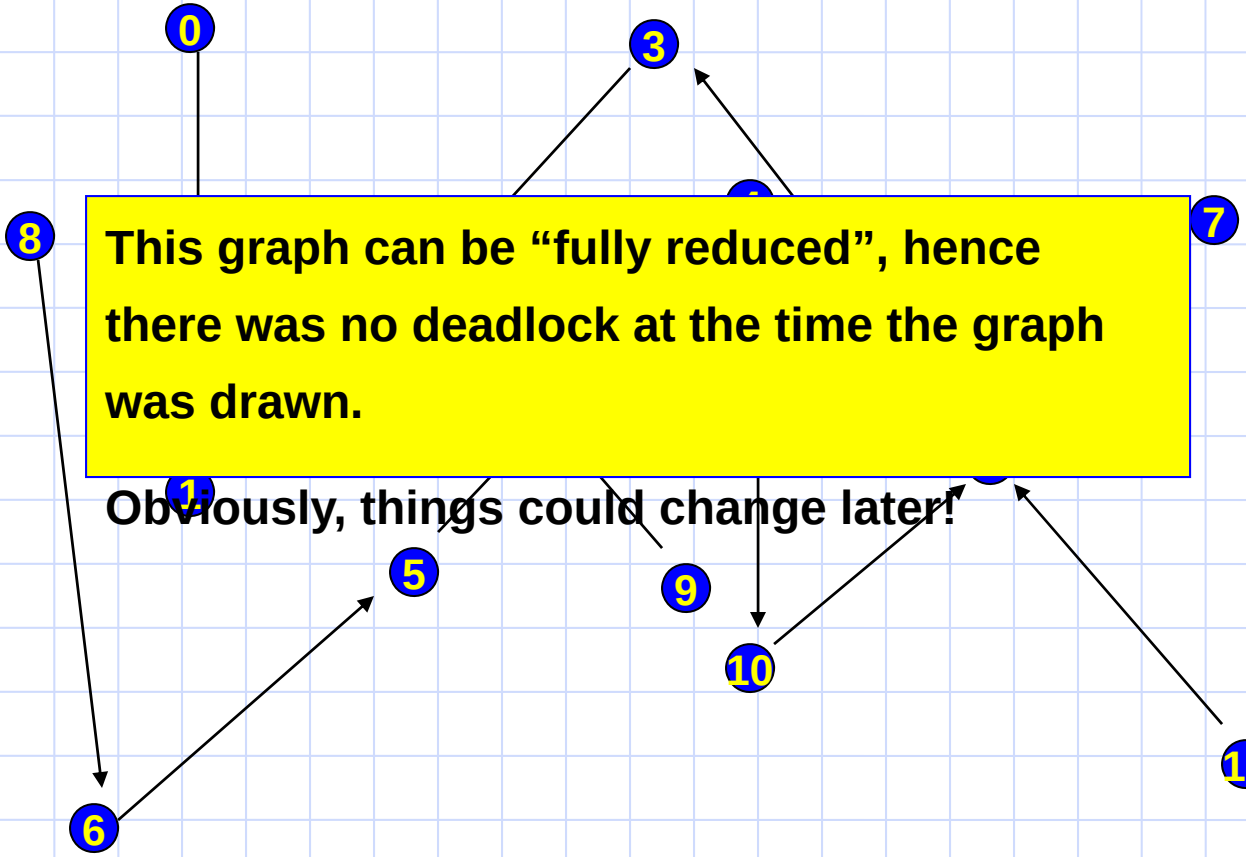
# Testing for deadlock

- Steps
  - Collect “process state” and use it to build a graph
    - Ask each process “are you waiting for anything”?
    - Put an edge in the graph if so
  - We need to do this in a single instant of time, not while things might be changing
- Now need a way to test for cycles in our graph

# Testing for deadlock

- One way to find cycles
  - Look for a node with no outgoing edges
  - Erase this node, and also erase any edges coming into it
    - Idea: This was a process people might have been waiting for, but it wasn't waiting for anything else
  - If (and only if) the graph has no cycles, we'll eventually be able to erase the whole graph!
- This is called a graph reduction algorithm

# Graph reduction example

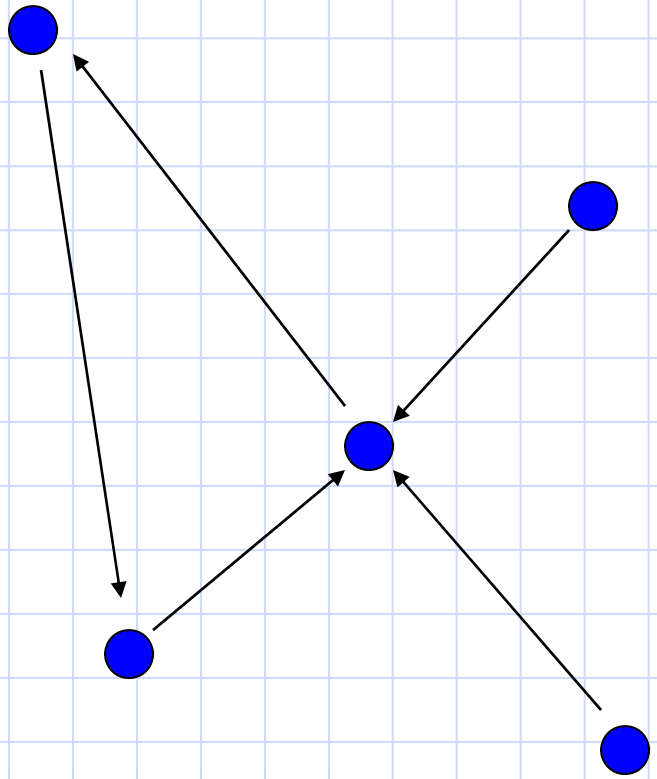



**This graph can be “fully reduced”, hence there was no deadlock at the time the graph was drawn.**

**Obviously, things could change later!**

# Graph reduction example

- This is an example of an “irreducible” graph
- It contains a cycle and represents a deadlock, although only some processes are in the cycle

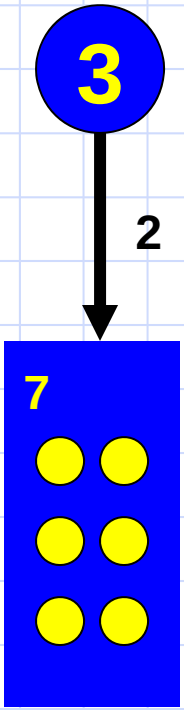


# What about “resource” waits?

- Processes usually don’t wait for each other.
- Instead, they wait for resources used by other processes.
  - Process A needs access to the critical section of memory process B is using
- Can we extend our graphs to represent resource wait?

# Resource-wait graphs

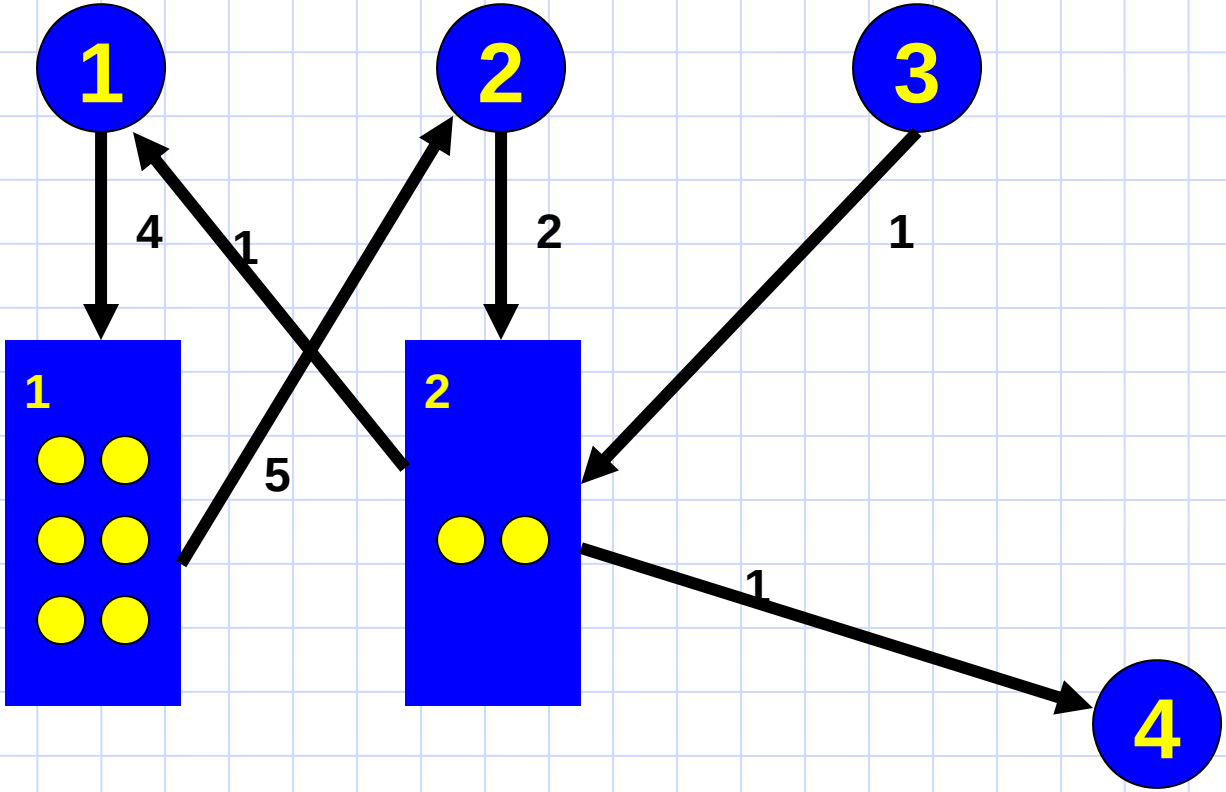
- We'll use two kinds of nodes
- A process: $P_3$ will be represented as:
- A resource: $R_7$ will be represented as:
  - A resource often has multiple identical units, such as "blocks of memory"
  - Represent these as circles in the box
- Arrow from a process to a resource: "I want *k* units of this resource." Arrow to a process: this process holds *k* units of the resource
  - $P_3$ wants 2 units of $R_7$



# A tricky choice...

- When should resources be treated as “different classes”?
  - To be in the same class, resources need to be equivalent
    - “memory pages” are different from “printers”
  - But for some purposes, we might want to split memory pages into two groups
    - Fast memory.  Slow memory
  - Proves useful in doing “ordered resource allocation”

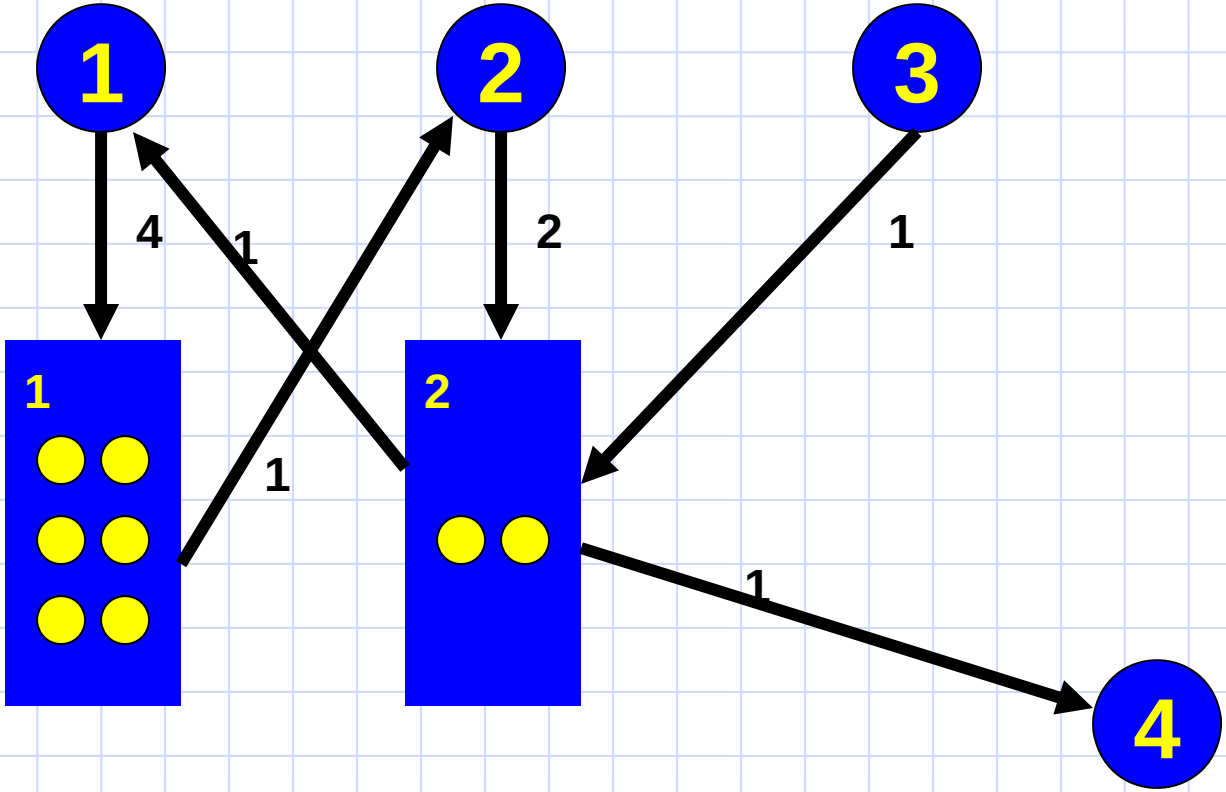
# Resource-wait graphs



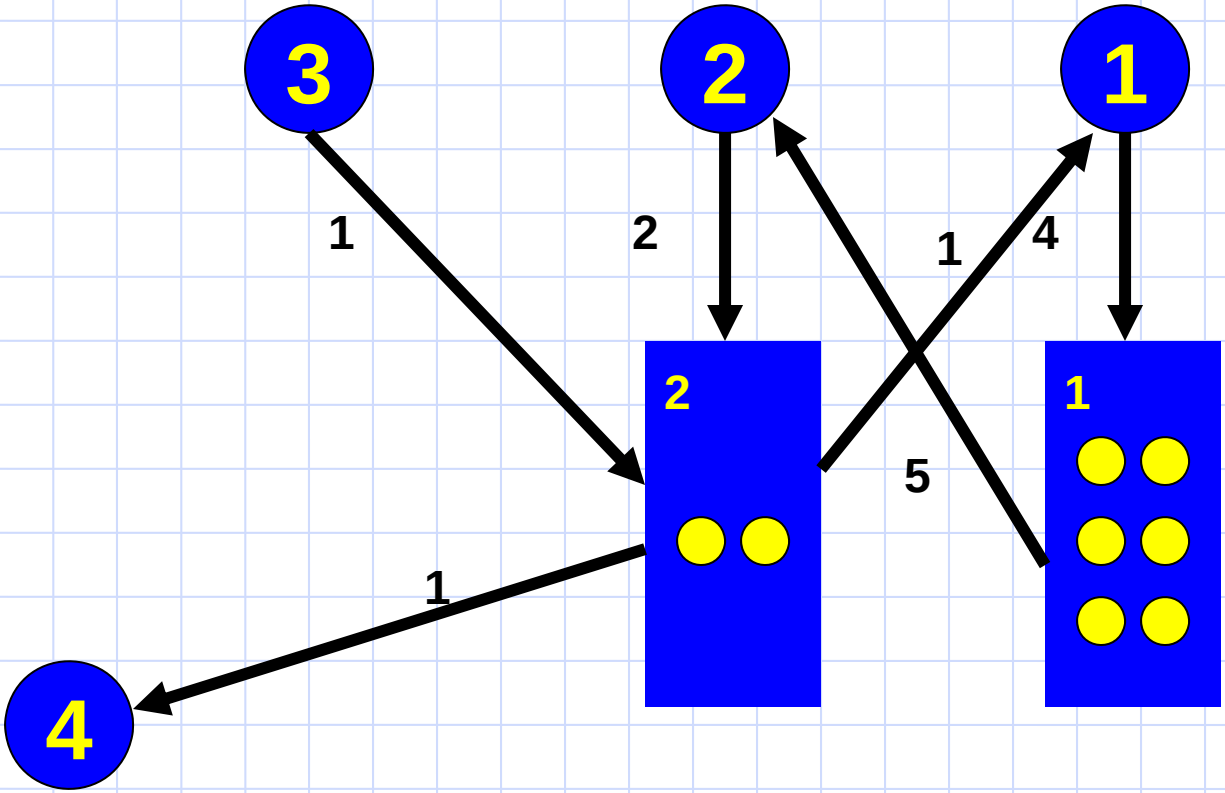
# Reduction rules?

- Find a process that can have all its current requests satisfied (e.g. the “available amount” of any resource it wants is at least enough to satisfy the request)
- Erase that process (in effect: grant the request, let it run, and eventually it will release the resource)
- Continue until we either erase the graph or have an irreducible component. In the latter case we’ve identified a deadlock

# This graph is reducible: The system is not deadlocked



# This graph is not reducible: The system is deadlocked



# Comments

- It isn't common for systems to actually implement this kind of test
- However, we'll use a version of the resource reduction graph as part of an algorithm called the "Banker's Algorithm".
- Idea is to schedule the granting of resources so as to avoid potentially deadlock states

# Some questions you might ask

- Does the order in which we do the reduction matter?
  - Answer: No. The reason is that if a node is a candidate for reduction at step i, and we don't pick it, it remains a candidate for reduction at step i+1
  - Thus eventually, no matter what order we do it in, we'll reduce by every node where reduction is feasible

# Some questions you might ask

- If a system is deadlocked, could the deadlock go away on its own?
  - No, unless someone kills one of the threads or something causes a process to release a resource
  - Many real systems put time limits on “waiting” precisely for this reason. When a process gets a timeout exception, it gives up waiting and this also can eliminate the deadlock
  - But that process may be forced to terminate itself because often, if a process can’t get what it needs, there are no other options available!

# Some questions you might ask

- Suppose a system isn't deadlocked at time T
- Can we assume it will still be free of deadlock at time T+1?
  - No, because the very next thing it might do is to run some process that will request a resource...
    - ... establishing a cyclic wait
    - ... and causing deadlock

# Dealing with Deadlocks

1. Reactive Approaches:
   - Periodically check for evidence of deadlock
     - For example, using a graph reduction algorithm
   - Then need a way to recover
     - Could blue screen and reboot the computer
     - Could pick a “victim” and terminate that thread
       - But this is only possible in certain kinds of applications
       - Basically, thread needs a way to clean up if it gets terminated and has to exit in a hurry!
     - Often thread would then “retry” from scratch

(despite drawbacks, database systems do this)

# Dealing with Deadlocks

2. Proactive Approaches:
   - Deadlock Prevention and Avoidance
     - Prevent one of the 4 necessary conditions from arising
     - .... This will prevent deadlock from occurring

# Deadlock Prevention

# Deadlock Prevention

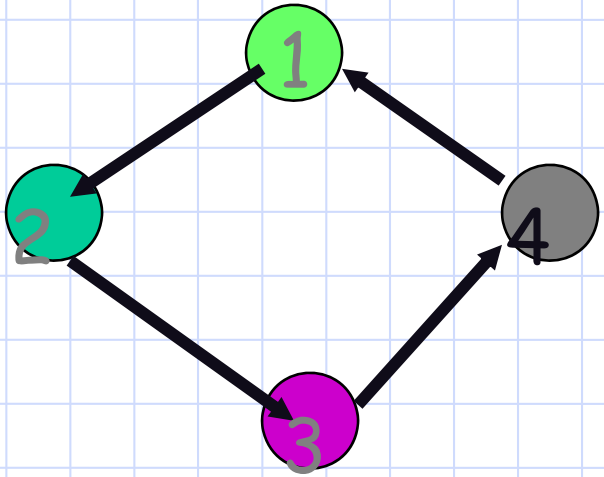
- Can the OS prevent deadlocks?
- Prevention: Negate one of necessary conditions
  - Mutual exclusion:
    - Make resources sharable
    - Not always possible (printers?)
  - Hold and wait
    - Do not hold resources when waiting for another
    - ⇒ Request all resources before beginning execution
    - Processes do not know what all they will need
    - Starvation (if waiting on many popular resources)
    - Low utilization (Need resource only for a bit)
    - Alternative: Release all resources before requesting anything new
      - Still has the last two problems

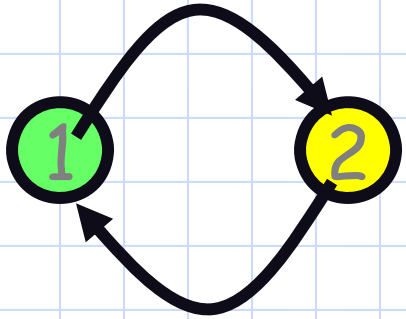
# Deadlock Prevention

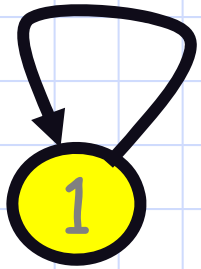
- Prevention: Negate one of necessary conditions
  - No preemption:
    - Make resources preemptable (2 approaches)
      - Preempt requesting processes' resources if all not available
      - Preempt resources of waiting processes to satisfy request
    - Good when easy to save and restore state of resource
      - CPU registers, memory virtualization
  - Circular wait: (2 approaches)
    - Single lock for entire system? (Problems)
    - Impose partial ordering on resources, request them in order

# Deadlock Prevention

- Prevention: Breaking circular wait
  - Order resources (lock1, lock2, ...)
  - Acquire resources in strictly increasing/decreasing order
  - When requests to multiple resources of same order:
    - Make the request a single operation
  - Intuition: Cycle requires an edge from low to high, and from high to low numbered node, or to same node




  - Ordering not always possible, low resource utilization

# Deadlock Avoidance

# Deadlock Avoidance

- If we have future information
  - Max resource requirement of each process before they execute
- Can we guarantee that deadlocks will never occur?
- Avoidance Approach:
  - Before granting resource, check if state is **safe**
  - If the state is safe $\Rightarrow$ no deadlock!

# Safe State

- A state is said to be **safe**, if it has a process sequence

  $\{P_1, P_2, \ldots, P_n\}$, such that for each $P_i$,

  the resources that $P_i$ can still request can be satisfied by the currently available resources plus the resources held by all $P_j$, where $j < i$

- State is safe because OS can definitely avoid deadlock
  - by blocking any new requests until safe order is executed

- This avoids circular wait condition
  - Process waits until safe state is guaranteed

# Safe State Example

- Suppose there are 12 tape drives

| | max need | current usage | could ask for |
|---|---|---|---|
| p0 | 10 | 5 | 5 |
| p1 | 4 | 2 | 2 |
| p2 | 9 | 2 | 7 |

3 drives remain

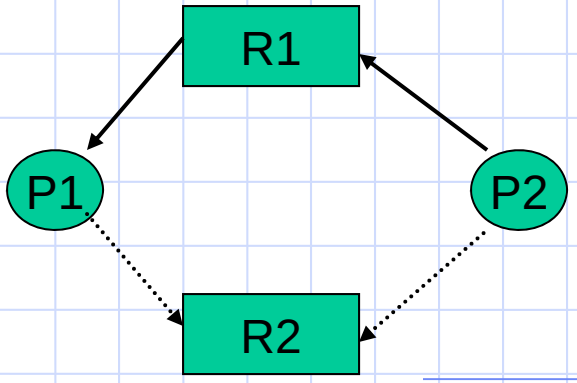
- current state is safe because a safe sequence exists: <p1,p0,p2>
  - p1 can complete with current resources
  - p0 can complete with current+p1
  - p2 can complete with current +p1+p0

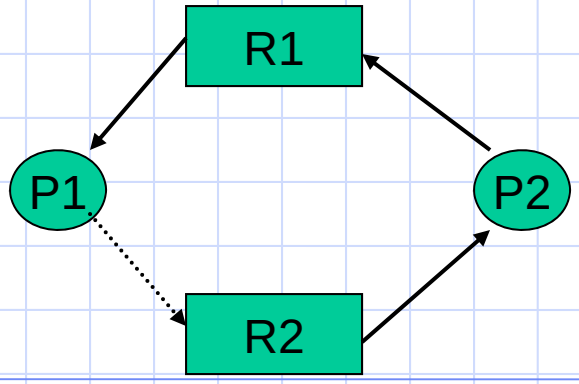
- if p2 requests 1 drive, then it must wait to avoid unsafe state.

# Res. Alloc. Graph Algorithm

- Works if only **one** instance of each resource type
- Algorithm:
  - Add a **claim edge**, $P_i \rightarrow R_j$ if $P_i$ can request $R_j$ in the future
    - Represented by a dashed line in graph
  - A request $P_i \rightarrow R_j$ can be granted only if:
    - Adding an assignment edge $R_j \rightarrow P_i$ does not introduce cycles

      (since cycles imply unsafe state)



# Res. Alloc. Graph issues:

- A little complex to implement
  - Would need to make it part of the system
  - E.g. build a “resource management” library
- Very conservative

# Banker's Algorithm

- Suppose we know the "worst case" resource needs of processes in advance
  - A bit like knowing the credit limit on your credit cards. (This is why they call it the Banker's Algorithm)
- Observation: Suppose we just give some process ALL the resources it could need...
  - Then it will execute to completion.
  - After which it will give back the resources.
- Like a bank: If Visa just hands you all the money your credit lines permit, at the end of the month, you'll pay your entire bill, right?

# Banker's Algorithm

- So...
  - A process pre-declares its worst-case needs
  - Then it asks for what it "really" needs, a little at a time
  - The algorithm decides when to grant requests
- It delays a request unless:
  - It can find a sequence of processes...
  - .... such that it could grant their outstanding need...
  - ... so they would terminate...
  - ... letting it collect their resources...
  - ... and in this way it can execute everything to completion!

# Banker's Algorithm

- How will it really do this?
  - The algorithm will just implement the graph reduction method for resource graphs
  - Graph reduction is "like" finding a sequence of processes that can be executed to completion
- So: given a request
  - Build a resource graph
  - See if it is reducible, only grant request if so
  - Else must delay the request until someone releases some resources, at which point can test again

# Banker's Algorithm

- Decides whether to grant a resource request.
- Data structures:

n: integer # of processes
m: integer # of resources
available[1..m] - available[i] is # of avail resources of type i
max[1..n,1..m] - max demand of each Pi for each Ri
allocation[1..n,1..m] - current allocation of resource Rj to Pi
need[1..n,1..m]max # resource Rj that Pi may still request

let request[i] be vector of # of resource Rj Process Pi wants

# Basic Algorithm

1. If request[i] > need[i] then

   error (asked for too much)

2. If request[i] > available[i] then

   wait (can't supply it now)

3. Resources are available to satisfy the request

   Let's assume that we satisfy the request. Then we would have:

   available = available - request[i]

   allocation[i] = allocation [i] + request[i]

   need[i] = need [i] - request [i]

   Now, check if this would leave us in a safe state:

   if yes, grant the request,

   if no, then leave the state as is and cause process to wait.

# Safety Check

free[1..m] = available /* how many resources are available */
finish[1..n] = false (for all i) /* none finished yet */

**Step 1:** Find an i such that finish[i]=false and need[i] <= work
/* find a proc that can complete its request now */
if no such i exists, go to step 3 /* we're done */

**Step 2:** Found an i:
finish [i] = true /* done with this process */
free = free + allocation [i]
/* assume this process were to finish, and its allocation back to the available list */
go to step 1

**Step 3:** If finish[i] = true for all i, the system is safe. Else Not

# Banker's Algorithm: Example

| | Allocation | | | Max | | | Available | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | A | B | C | A | B | C |
| P0 | 0 | 1 | 0 | 7 | 5 | 3 | 3 | 3 | 2 |
| P1 | 2 | 0 | 0 | 3 | 2 | 2 | | | |
| P2 | 3 | 0 | 2 | 9 | 0 | 2 | | | |
| P3 | 2 | 1 | 1 | 2 | 2 | 2 | | | |
| P4 | 0 | 0 | 2 | 4 | 3 | 3 | | | |

this is a safe state: safe sequence <P1, P3, P4, P2, P0>

Suppose that P1 requests (1,0,2)

- add it to P1's allocation and subtract it from Available

# Banker's Algorithm: Example

| | Allocation | | | Max | | | Available | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | A | B | C | A | B | C |
| P0 | 0 | 1 | 0 | 7 | 5 | 3 | 2 | 3 | 0 |
| P1 | 3 | 0 | 2 | 3 | 2 | 2 | | | |
| P2 | 3 | 0 | 2 | 9 | 0 | 2 | | | |
| P3 | 2 | 1 | 1 | 2 | 2 | 2 | | | |
| P4 | 0 | 0 | 2 | 4 | 3 | 3 | | | |

This is still safe: safe seq <P1, P3, P4, P0, P2>

In this new state,P4 requests (3,3,0)

not enough available resources

P0 requests (0,2,0)

let's check resulting state

# Banker's Algorithm: Example

| | Allocation | | | Max | | | Available | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | A | B | C | A | B | C |
| P0 | 0 | 3 | 0 | 7 | 5 | 3 | 2 | 1 | 0 |
| P1 | 3 | 0 | 2 | 3 | 2 | 2 | | | |
| P2 | 3 | 0 | 2 | 9 | 0 | 2 | | | |
| P3 | 2 | 1 | 1 | 2 | 2 | 2 | | | |
| P4 | 0 | 0 | 2 | 4 | 3 | 3 | | | |

This is unsafe state (why?)

So P0's request will be denied

Problems with Banker's Algorithm?

# The story so far..

- We saw that you can prevent deadlocks.
  - By negating one of the four necessary conditions. (which are..?)
- We saw that the OS can schedule processes in a careful way so as to avoid deadlocks.
  - Using a resource allocation graph.
  - Banker's algorithm.
  - What are the downsides to these?

# Deadlock Detection & Recovery

- If neither avoidance or prevention is implemented, deadlocks can (and will) occur.
- Coping with this requires:
  - Detection: finding out if deadlock has occurred
    - Keep track of resource allocation (who has what)
    - Keep track of pending requests (who is waiting for what)
  - Recovery: untangle the mess.
- Expensive to detect, as well as recover

# Using the RAG Algorithm to detect deadlocks

- Suppose there is only one instance of each resource
- Example 1: Is this a deadlock?
  - P1 has R2 and R3, and  is requesting R1
  - P2 has R4 and is requesting R3
  - P3 has R1 and is requesting R4
- Example 2: Is this a deadlock?
  - P1 has R2, and  is requesting R1 and R3
  - P2 has R4 and is requesting R3
  - P3 has R1 and is requesting R4
- Use a **wait-for graph:**
  - Collapse resources
  - An edge $P_i \rightarrow P_k$ exists only if RAG has $P_i \rightarrow R_j$ & $R_j \rightarrow P_k$
  - Cycle in wait-for graph $\Rightarrow$ deadlock!

# 2nd Detection Algorithm

- What if there are multiple resource instances?
- Data structures:

```
n: integer    # of processes
m: integer    # of resources
available[1..m]    available[i] is # of avail resources of type i
request[1..n,1..m]     current  demand of each Pi for each Ri
allocation[1..n,1..m]  current allocation of resource Rj to Pi
finish[1..n]              true if Pi's request can be satisfied

let request[i] be vector of # instances of each resource Pi wants
```

# 2nd Detection Algorithm

1. work[]=available[]

   for all i < n, if allocation[i] ≠ 0

   then finish[i]=false else finish[i]=true

2. find an index i such that:

   finish[i]=false;

   request[i]<=work

   if no such i exists, go to 4.

3. work=work+allocation[i]

   finish[i] = true, go to 2

4. if finish[i] = false for some i,

   then system is deadlocked with Pi in deadlock

# Example

Finished = {F, F, F, F};

Work = Available = (0, 0, 1);

| | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $P_1$ | 1 | 1 | 1 |
| $P_2$ | 2 | 1 | 2 |
| $P_3$ | 1 | 1 | 0 |
| $P_4$ | 1 | 1 | 1 |

Allocation

| | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $P_1$ | 3 | 2 | 1 |
| $P_2$ | 2 | 2 | 1 |
| $P_3$ | 0 | 0 | 1 |
| $P_4$ | 1 | 1 | 1 |

Request

# Example

Finished = {F, F, T, F};

Work = (1, 1, 1);

| | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $P_1$ | 1 | 1 | 1 |
| $P_2$ | 2 | 1 | 2 |
| $P_3$ | 1 | 1 | 0 |
| $P_4$ | 1 | 1 | 1 |

Allocation

| | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $P_1$ | 3 | 2 | 1 |
| $P_2$ | 2 | 2 | 1 |
| $P_3$ | | | |
| $P_4$ | 1 | 1 | 1 |

Request

# Example

Finished = {F, F, T, T};

Work = (2, 2, 2);

| | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $P_1$ | 1 | 1 | 1 |
| $P_2$ | 2 | 1 | 2 |
| $P_3$ | 1 | 1 | 0 |
| $P_4$ | 1 | 1 | 1 |

Allocation

| | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $P_1$ | 3 | 2 | 1 |
| $P_2$ | 2 | 2 | 1 |
| $P_3$ | | | |
| $P_4$ | | | |

Request

# Example

Finished = {F, T, T, T};

Work = (4, 3, 2);

| | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $P_1$ | 1 | 1 | 1 |
| $P_2$ | 2 | 1 | 2 |
| $P_3$ | 1 | 1 | 0 |
| $P_4$ | 1 | 1 | 1 |

Allocation

| | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $P_1$ | 3 | 2 | 1 |
| $P_2$ | | | |
| $P_3$ | | | |
| $P_4$ | | | |

Request

# When to run Detection Algorithm?

- For every resource request?
- For every request that cannot be immediately satisfied?
- Once every hour?
- When CPU utilization drops below  40%?

# Deadlock Recovery

- Killing one/all deadlocked processes
  - Crude, but effective
  - Keep killing processes, until deadlock broken
  - Repeat the entire computation
- Preempt resource/processes until deadlock broken
  - Selecting a victim (# resources held, how long executed)
  - Rollback (partial or total)
  - Starvation (prevent a process from being executed)