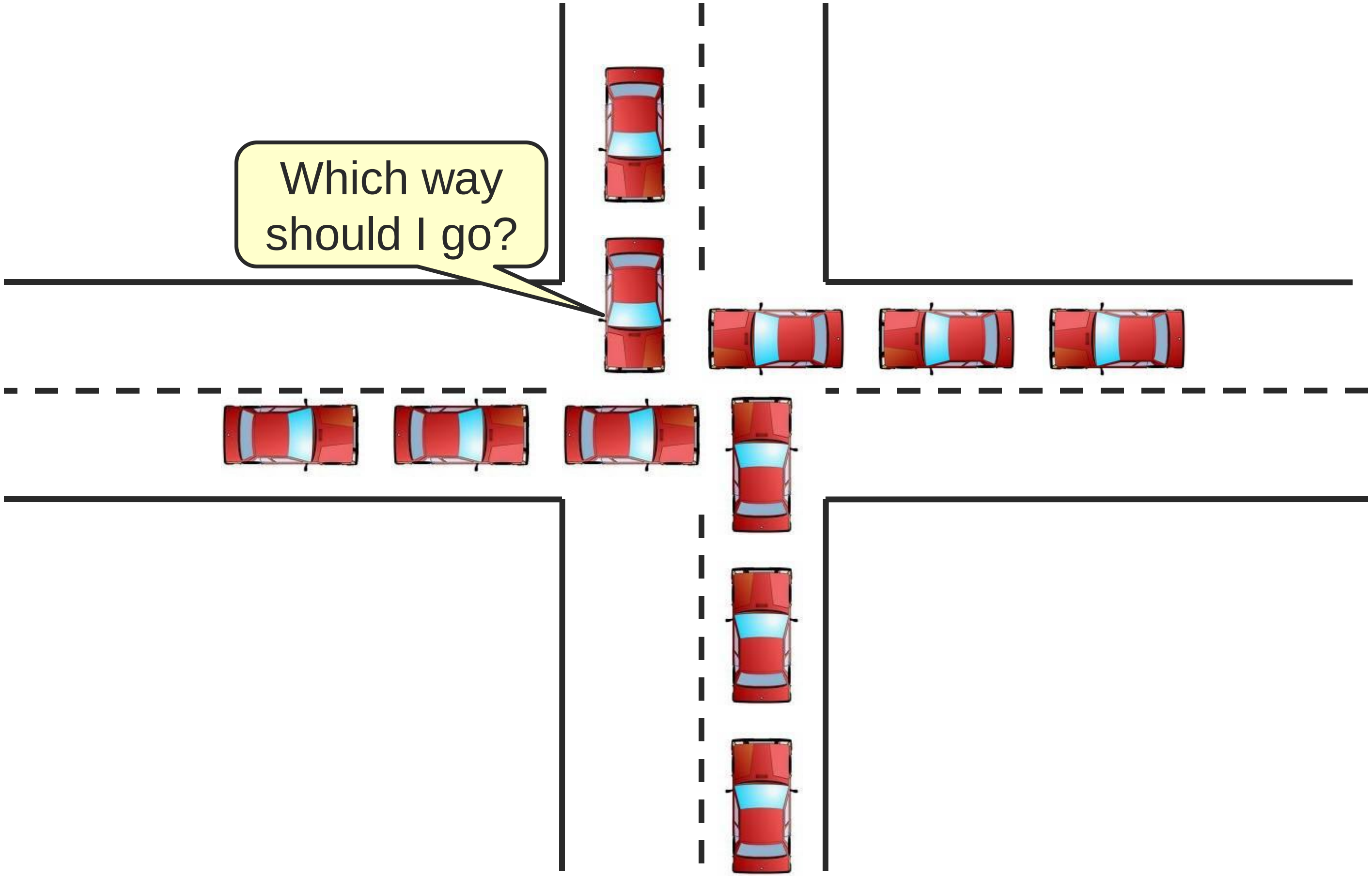
Deadlocks

Deadlock



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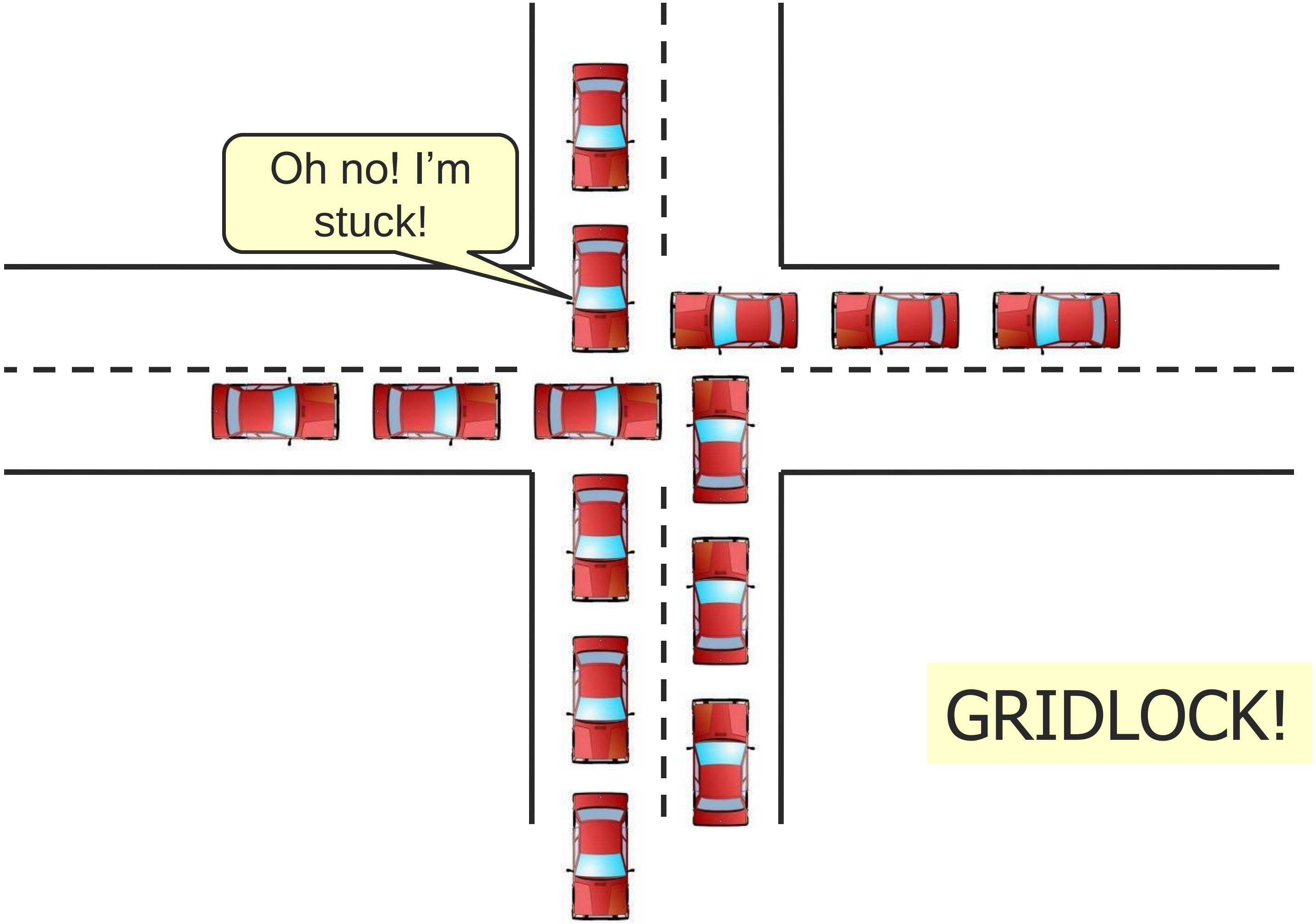
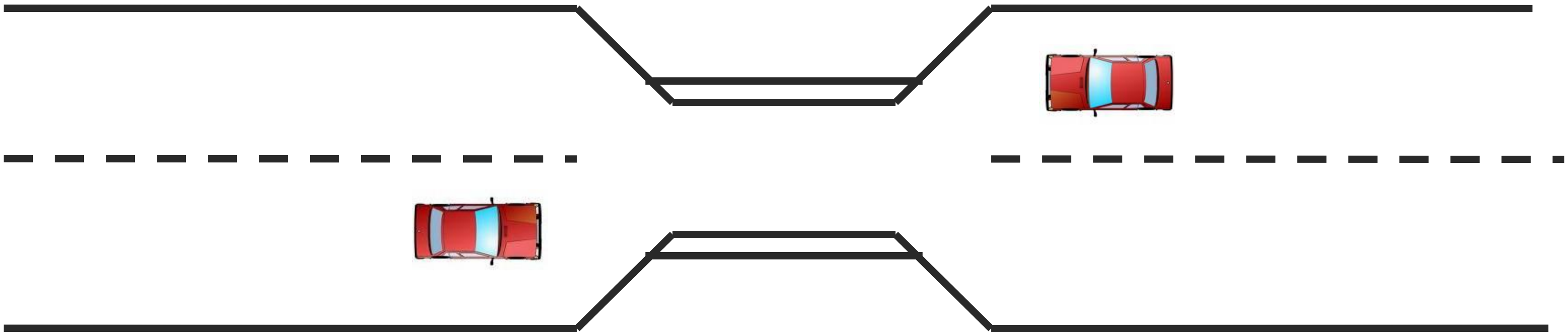


Deadlock Definition

- Deadlocked process
  - Waiting for an event that will never occur
  - Typically, but not necessarily, involves more than one process
    - A set of processes is deadlocked if each process in the set is waiting for an event that only another process in the set can cause

How can a single process deadlock itself?

Deadlock: One-lane Bridge



- Traffic only in one direction
- Each section of a bridge can be viewed as a resource

What can happen?

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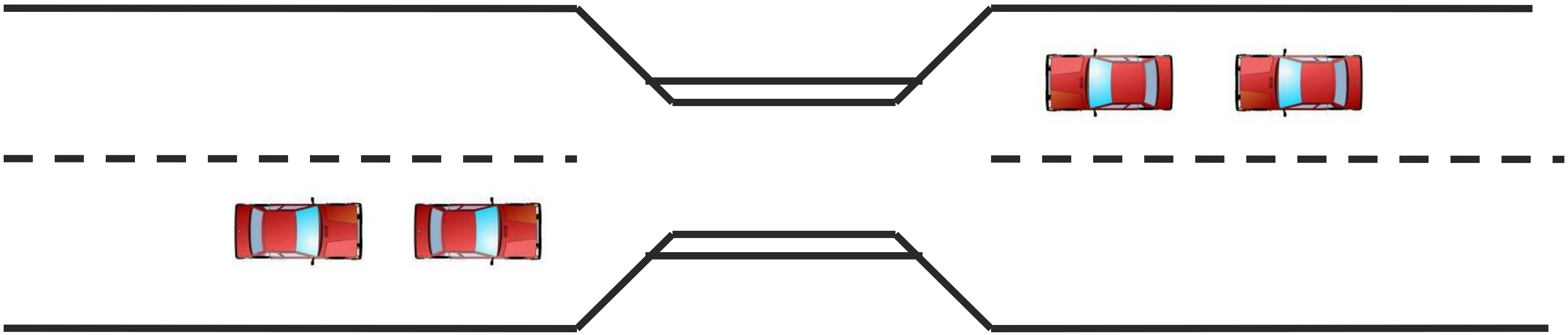
Deadlock: One-lane Bridge



- Traffic only in one direction
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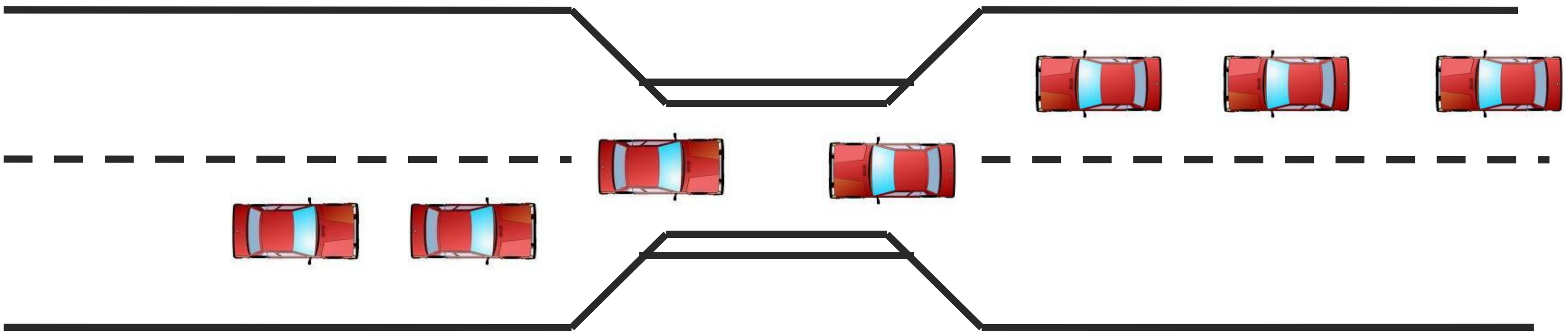
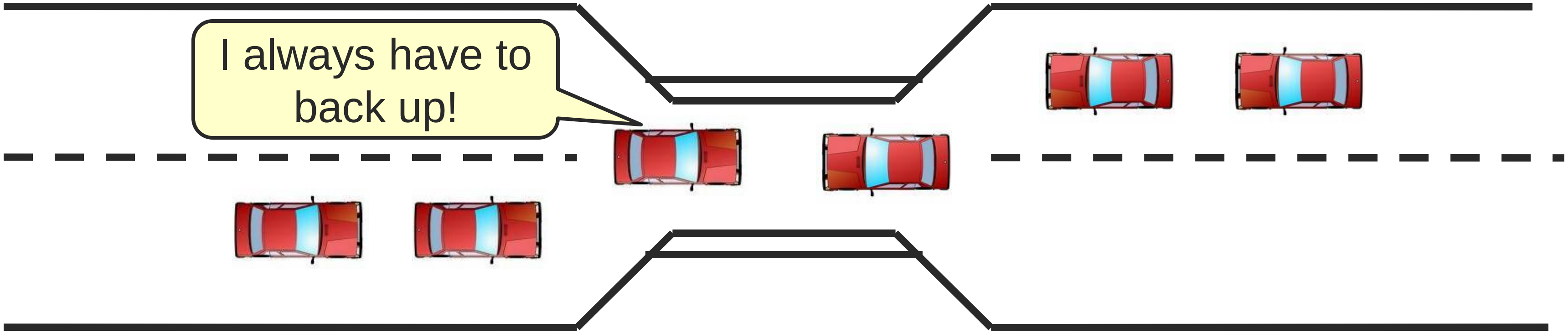
- Deadlock
  - Resolved if cars back up (preempt resources and rollback)
  - Several cars may have to be backed up

Deadlock: One-lane Bridge



- Traffic only in one direction
- Each section of a bridge can be viewed as a resource
- Deadlock
  - Resolved if cars back up (preempt resources and rollback)
  - Several cars may have to be backed up
- But, starvation is possible
  - e.g., if the rule is that Westbound cars always go first
- Note
  - Most OSes do not prevent or deal with deadlocks

Deadlock: One-lane Bridge



- Deadlock vs. Starvation
  - Starvation = Indefinitely postponed
    - Delayed repeatedly over a long period of time while the attention of the system is given to other processes
    - Logically, the process may proceed but the system never gives it the CPU

Addressing Deadlock

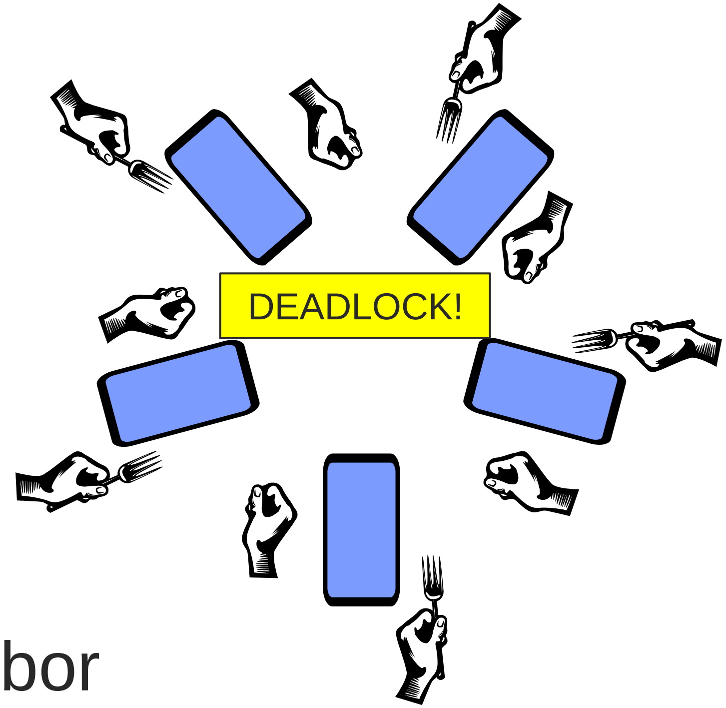
- Prevention
  - Design the system so that deadlock is impossible
- Detection & Recovery
  - Check for deadlock (periodically or sporadically) and identify and which processes and resources involved
  - Recover by killing one of the deadlocked processes and releasing its resources
- Avoidance
  - Construct a model of system states, then choose a strategy that, when resources are assigned to processes, will not allow the system to go to a deadlock state
- Manual intervention
  - Have the operator reboot the machine if it seems too slow

Necessary Conditions for Deadlock

- Mutual exclusion
  - Processes claim exclusive control of the resources they require
- Hold-and-wait (a.k.a. wait-for) condition
  - Processes hold resources already allocated to them while waiting for additional resources
- No preemption condition
  - Resources cannot be removed from the processes holding them until used to completion
- Circular wait condition
  - A circular chain of processes exists in which each process holds one or more resources that are requested by the next process in the chain

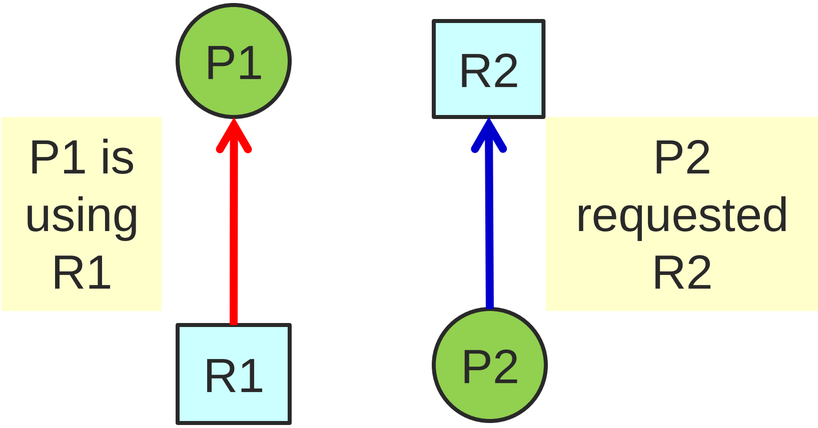
Dining Philosophers had it all

- Mutual exclusion
  - Exclusive use of forks
- Hold and wait condition
  - Hold 1 fork, wait for next
- No preemption condition
  - Cannot force another to undo their hold
- Circular wait condition
  - Each waits for next neighbor to put down fork



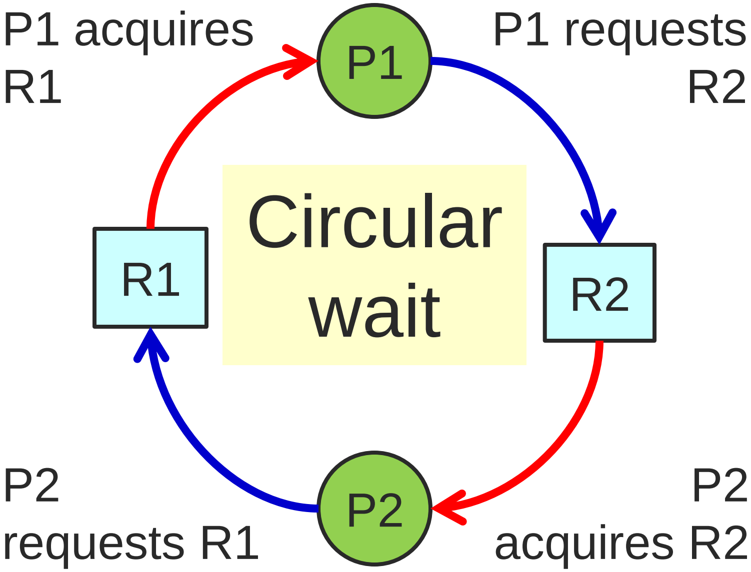
This is the best one to tackle

Formalizing circular wait: Resource allocation graphs



- Nodes
  - Circle: Processes
  - Square: Resources
- Arcs
  - From resource to process = resource assigned to process
  - From process to resource = process requests (and is waiting for) resource

Resource allocation graphs



- Nodes
  - Circle: Processes
  - Square: Resources
- Deadlock
  - Processes P1 and P2 are in deadlock over resources R1 and r2

Dining Philosophers resource allocation graph

If we use the trivial broken “solution”...

```
# define N 5

void philosopher (int i) {
   while (TRUE) {
      think();
      take_fork(i);
      take_fork((i+1)%N);
      eat(); /* yummy */
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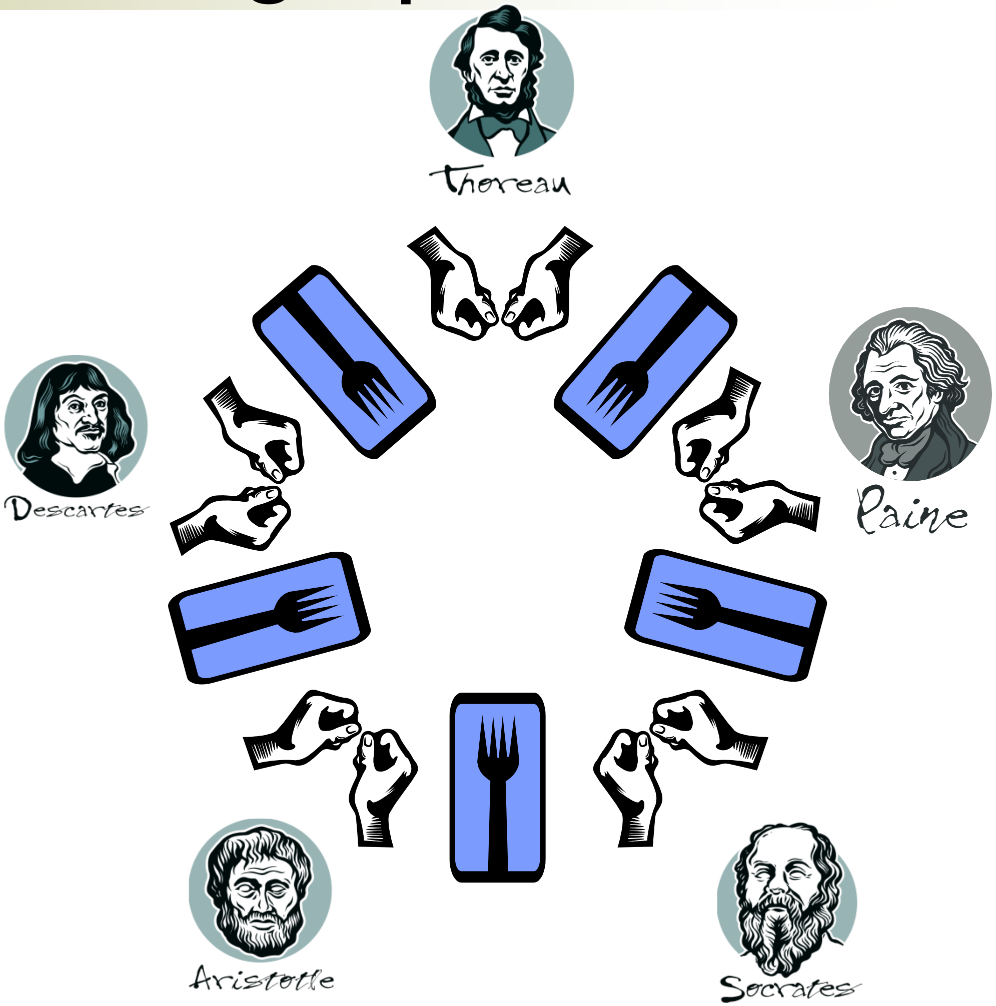


Dining Philosophers resource allocation graph

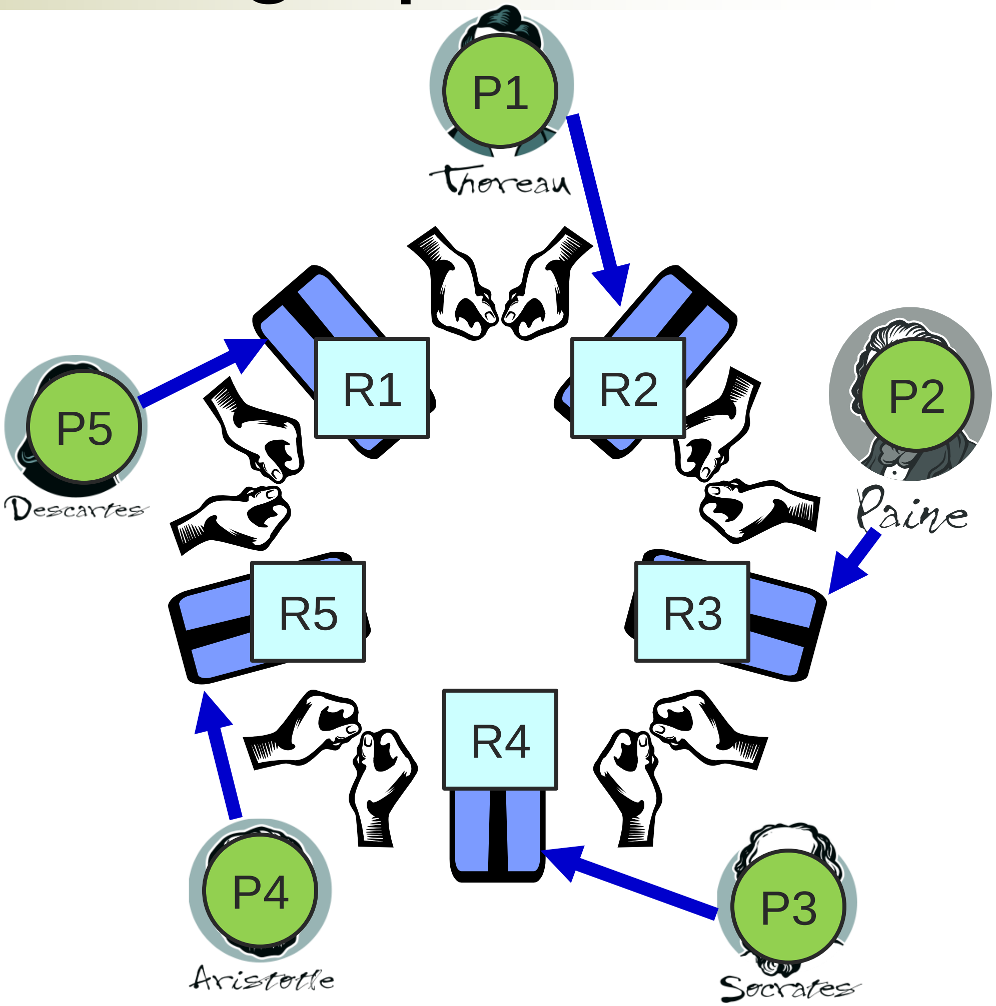
If we use the trivial broken "solution"...

One node per philosopher

One node per fork

⇒ Everyone tries to pick up left fork

⇒ Request edges



Dining Philosophers resource allocation graph

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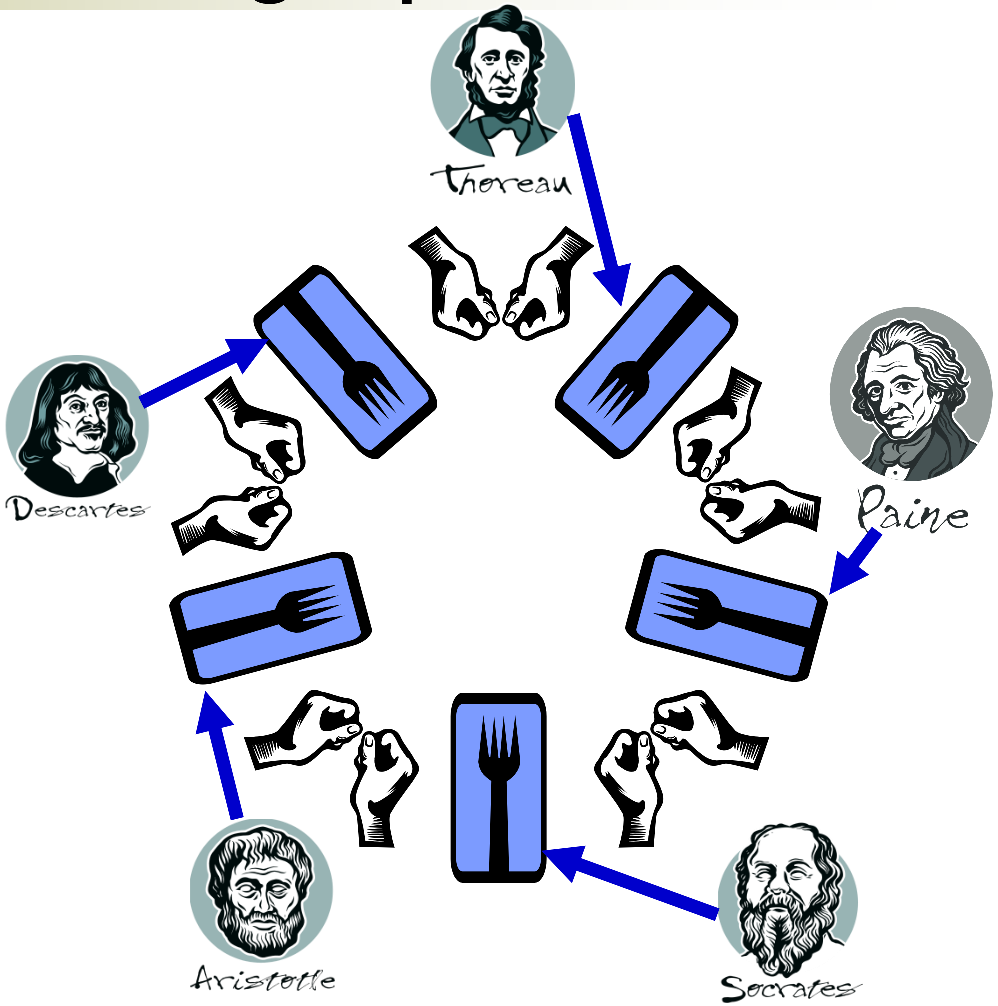
⇒ Everyone tries to pick up left fork

⇒ Everyone succeeds



Dining Philosophers resource allocation graph

If we use the trivial broken "solution"...

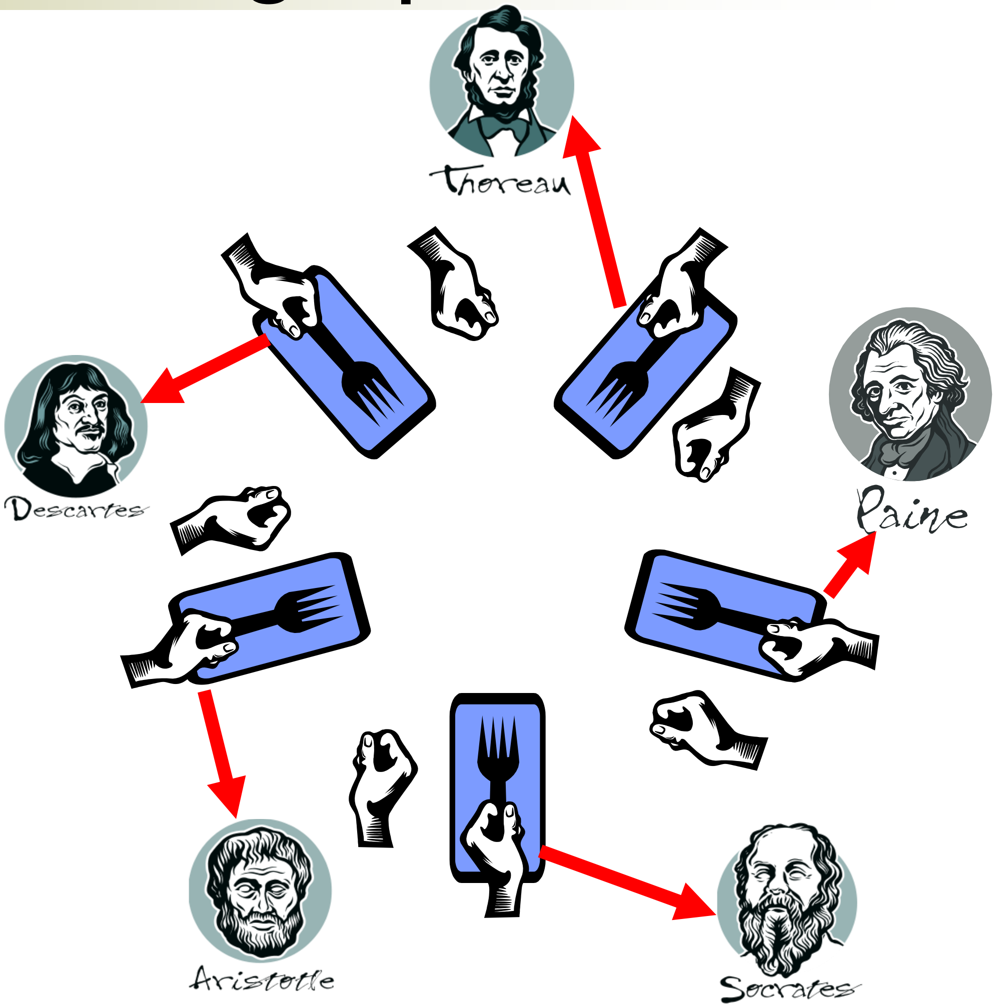
One node per philosopher

One node per fork

⇒ Everyone tries to pick up left fork

⇒ Everyone succeeds

⇒ Assignment edges



Dining Philosophers resource allocation graph

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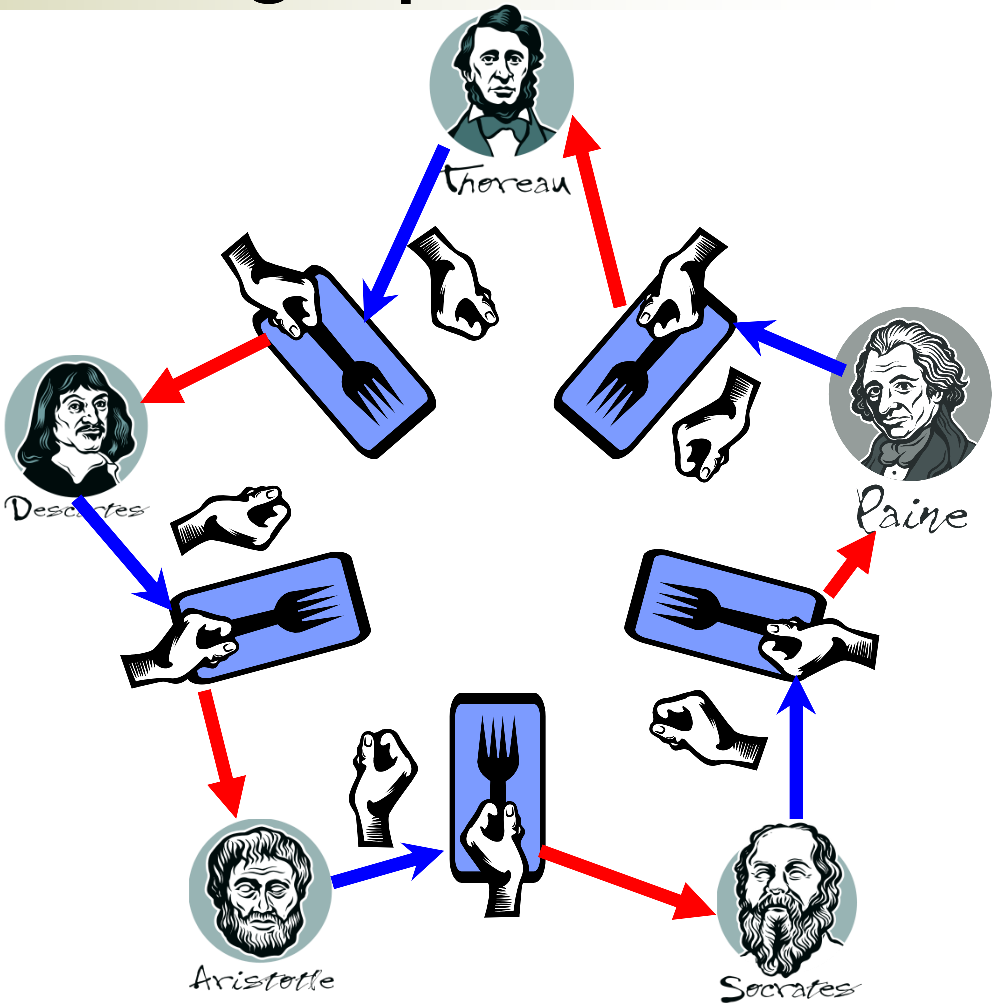
⇒ Everyone succeeds

⇒ Everyone tries to pick up right fork

⇒ Request edges



Dining Philosophers resource allocation graph

If we use the trivial broken "solution"...

One node per philosopher

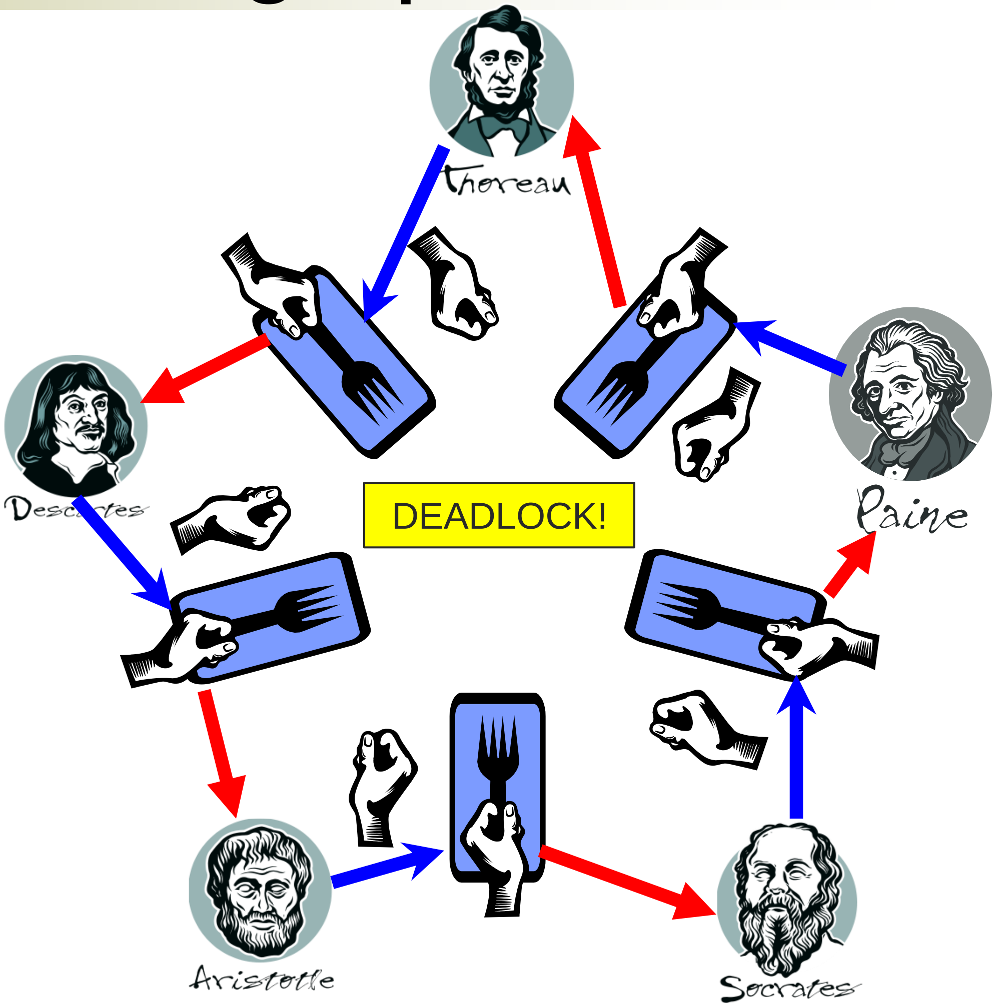
One node per fork

⇒Everyone tries to pick up left fork

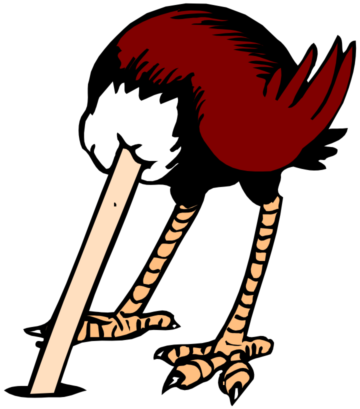
⇒ Everyone succeeds

⇒Everyone tries to pick up right fork

⇒ Cycle = deadlock



Default Solution: Be an Ostrich



- Approach
  - Do nothing!
  - Deadlocked processes stay stuck
- Rationale
  - Keeps the common path faster and more reliable
  - Deadlock prevention, avoidance and detection/recovery are expensive
  - If deadlock is rare, is it worth the overhead?

Deadlock Prevention

- Goal 1: devise resource allocation rules that make circular wait impossible
  - Resources include mutex locks, semaphores, pages of memory, ...
  - ...but you can think about just mutex locks for now

- Goal 2: make sure useful behavior is still possible!
  - The rules will necessarily be conservative
    - Rule out some behavior that would not cause deadlock
  - But they shouldn’t be to be too conservative
    - We still need to get useful work done

Deadlock Prevention

- Prevent any one of the 4 conditions
  - Mutual exclusion
  - Hold-and-wait
  - No preemption
  - Circular wait

Mutual Exclusion

- Processes claim exclusive control of the resources they require
- How to break it?

Mutual Exclusion

- Processes claim exclusive control of the resources they require
- How to break it?
  - Non-exclusive access only
    - Read-only access
  - Probably not an option for most scenarios
    - But be smart and try to use shared resources wisely
  - Battle won!
    - War lost
    - Very bad at Goal #2

Hold and Wait Condition

- Processes hold resources already allocated to them while waiting for additional resources
- How to break it?

Hold and Wait Condition

- Processes hold resources already allocated to them while waiting for additional resources
- How to break it?
  - All at once
    - Force a process to request all resources it needs at one time
    - Get all or nothing
  - Release and try again
    - If a process needs to acquire a new resource, it must first release all resources it holds, then reacquire all it needs
  - Both
    - Inefficient
    - Potential of starvation

Hold and Wait Condition

- Processes hold resources already allocated to them while waiting for additional resources
- How to break it?
    - Only one
        - Process can only have one resource locked
- Result
    - No circular wait!

Hold and Wait Condition

- Processes hold resources already allocated to them while waiting for additional resources
- Result
  - No circular wait!
  - Very constraining (mediocre job on Goal #2)
    - Better than Rules #1 and #2, but...
    - Often need more than one resource
    - Hard to predict resource needs at the beginning
    - Releasing and re-requesting is inefficient, complicates programming, might lead to starvation

No Preemption Condition

- Resources cannot be taken from processes holding them until used to completion
- How to break it?

No Preemption Condition

- Resources cannot be taken from processes holding them until used to completion
- How to break it?
  - Let it all go
    - If a process holding some resources is denied a further request, that process must release its original resources
    - Inefficient!
  - Take it all away
    - If a process requests a resource that is held by another process, the OS may preempt the second process and force it to release its resources
    - Waste of CPU and other resources!

No Preemption Condition

- Resources cannot be taken from processes holding them until used to completion
- Result
  - Breaks circular wait
    - Because we don’t have to wait
  - Reasonable strategy sometimes
    - e.g. if resource is memory: “preempt” = page to disk
  - Not so convenient for synchronization resources
    - e.g., locks in multithreaded application
    - What if current owner is in the middle of a critical section updating pointers? Data structures might be left in inconsistent state!

Circular Wait Condition

- A circular chain of processes exists in which each process holds one or more resources that are requested by the next process in the chain
- How to break it?

Circular Wait Condition

- A circular chain of processes exists in which each process holds one or more resources that are requested by the next process in the chain
- How to break it?
  - Guarantee no cycles
    - Allow processes to access resources only in increasing order of resource id
    - Not really fair or necessarily efficient …

Dining Philosophers solution with numbered resources

Back to the trivial broken "solution"...

```
# define N 5

void philosopher (int i) {
   while (TRUE) {
      think();
      take_fork(i);
      take_fork((i+1)%N);
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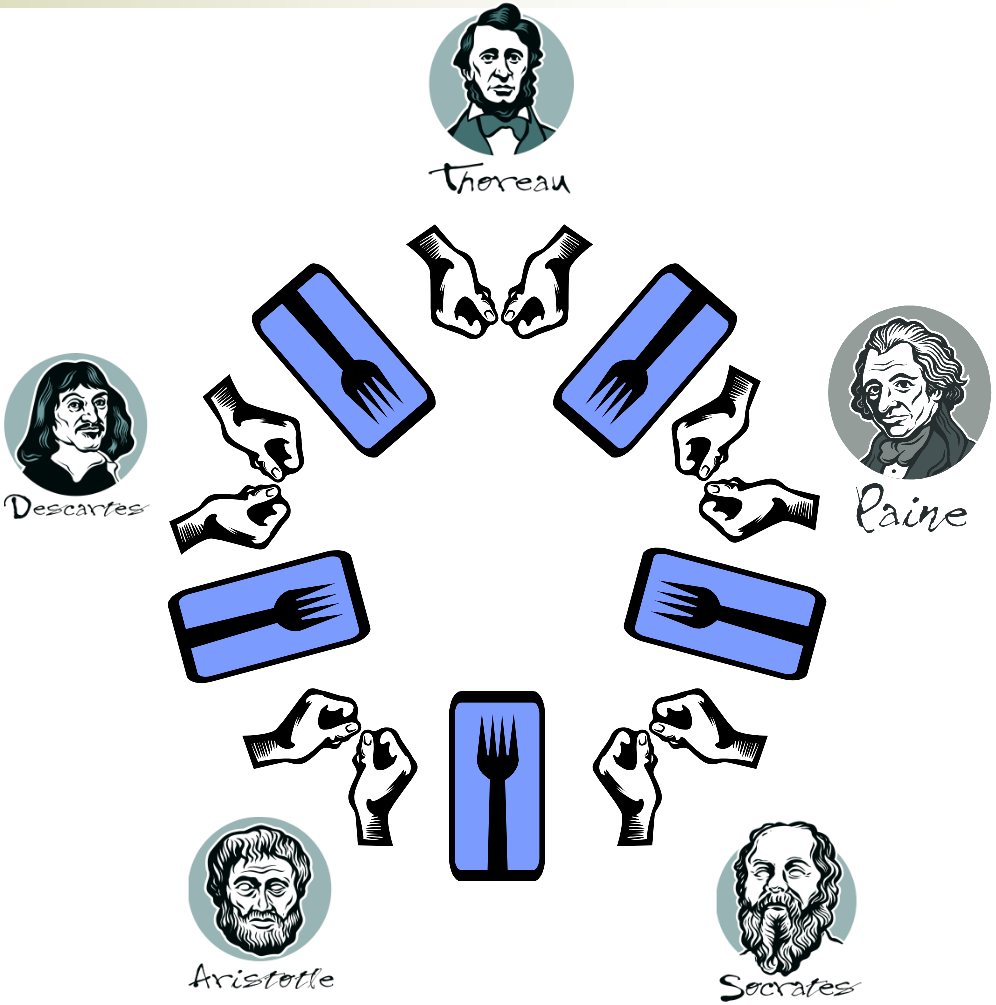

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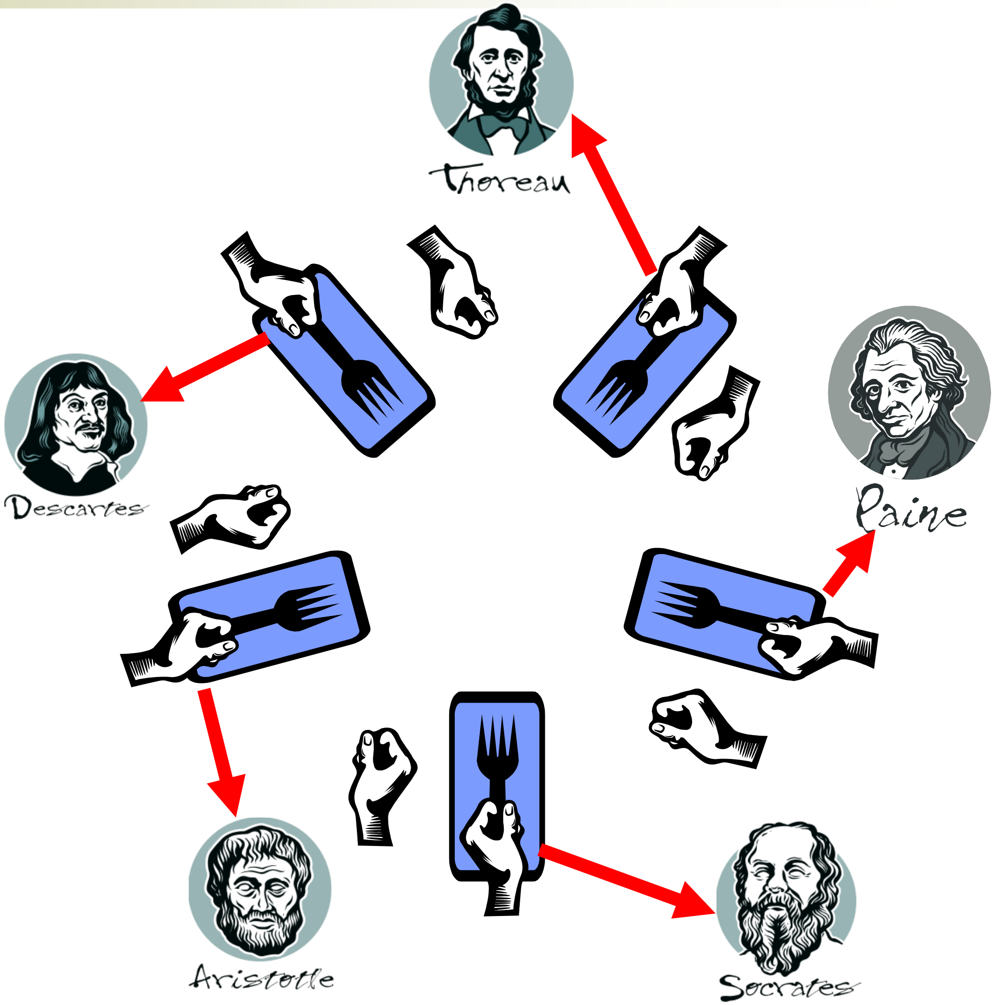

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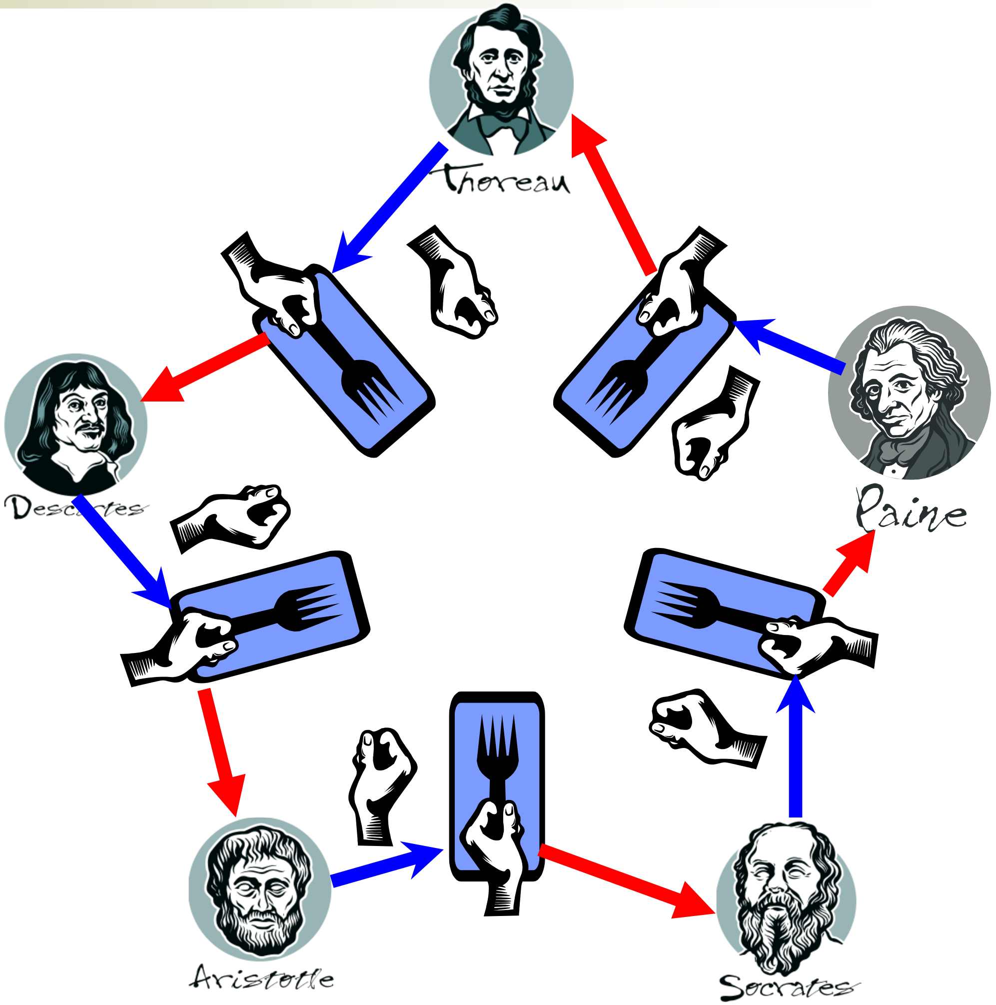

Dining Philosophers solution with numbered resources

Instead, number resources...

First request lower numbered fork

```
# define N 5

void philosopher (int i) {
    while (TRUE) {
        think();
        take_fork(LOWER(i));
        take_fork(HIGHER(i));
        eat(); /* yummy */
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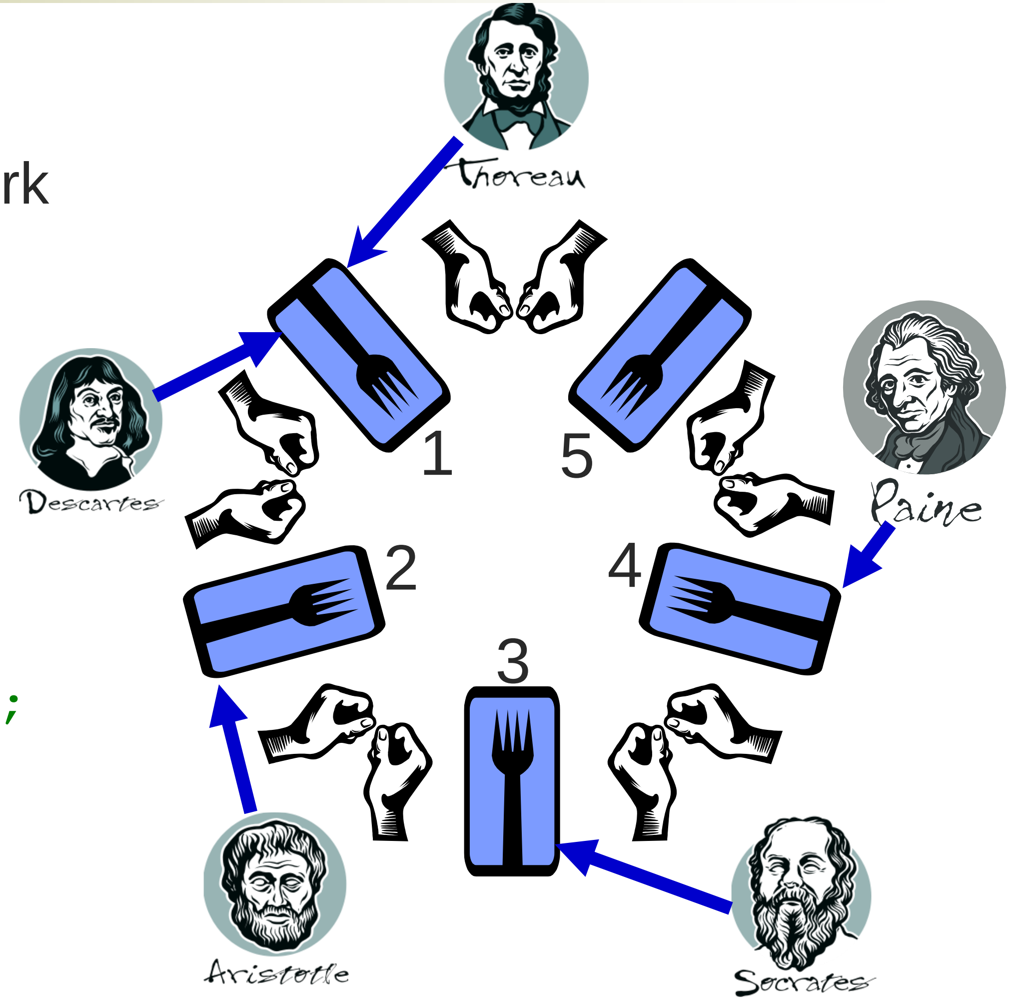

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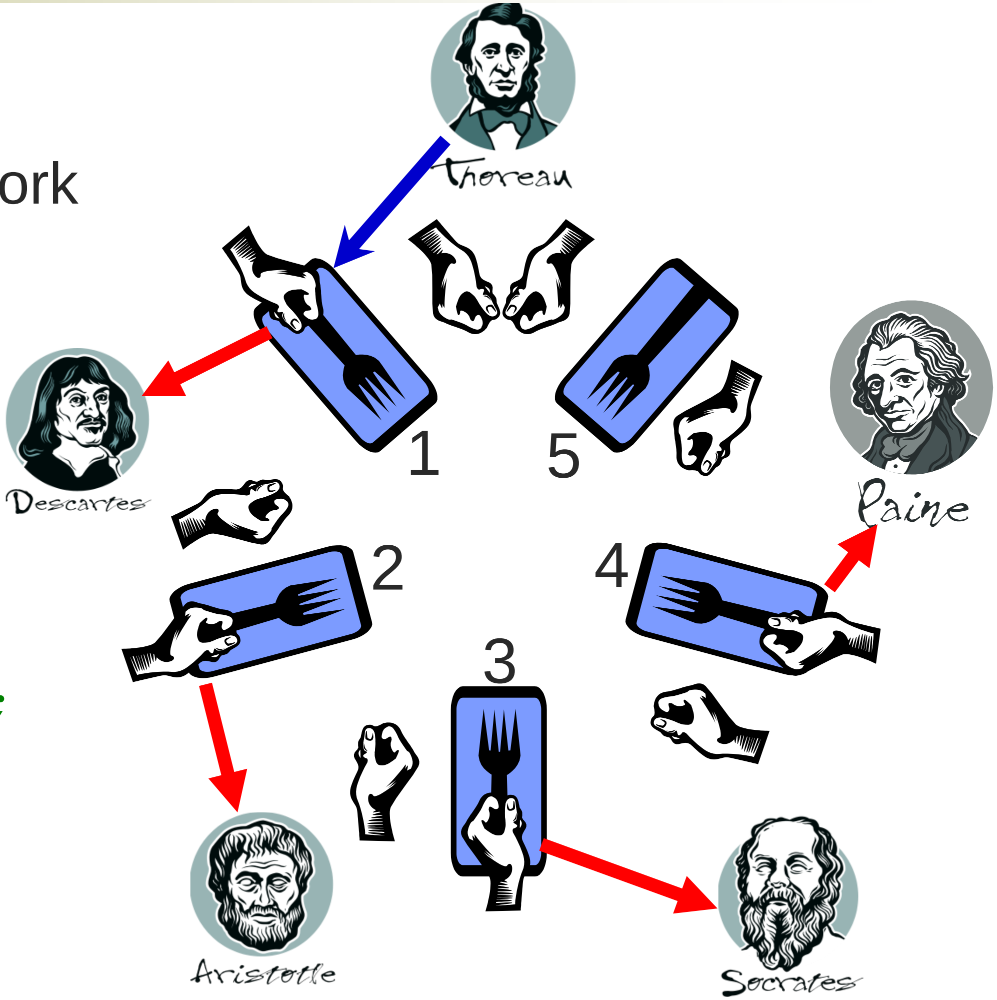

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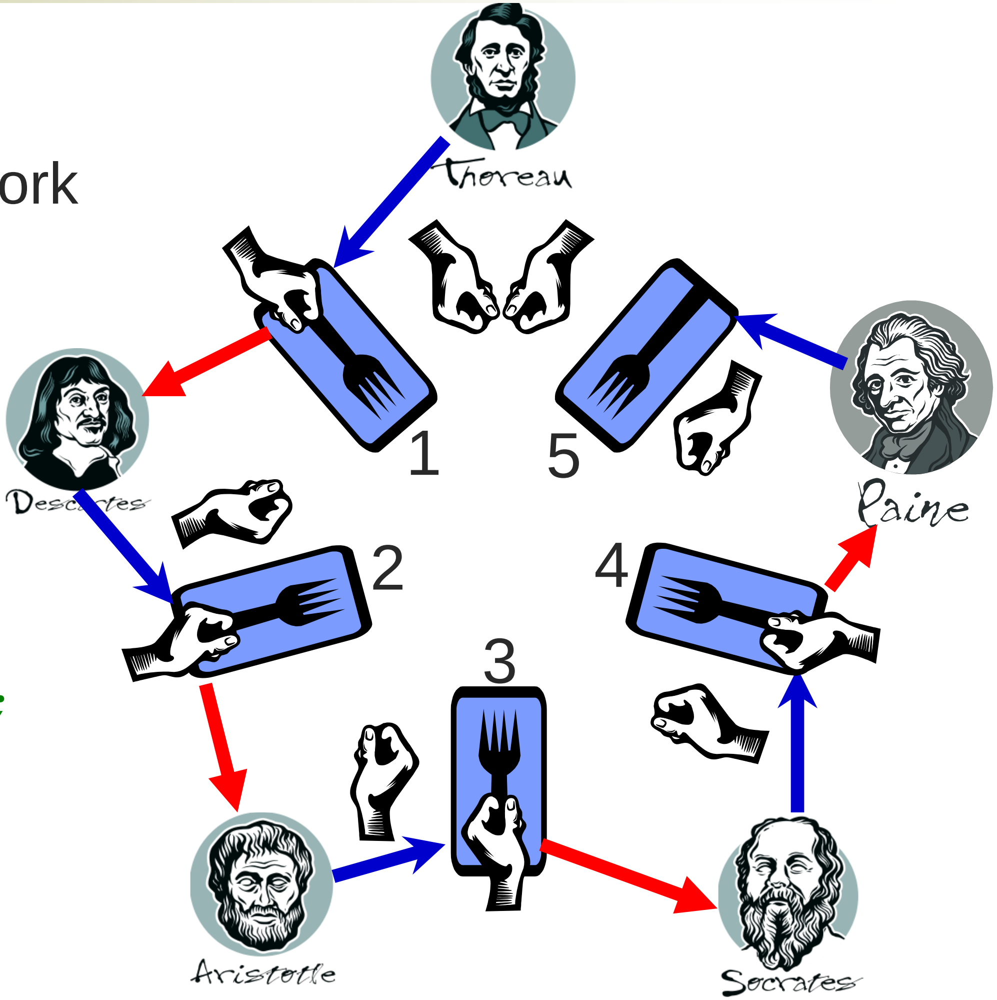

Dining Philosophers solution with numbered resources

Instead, number resources...

One philosopher can eat!

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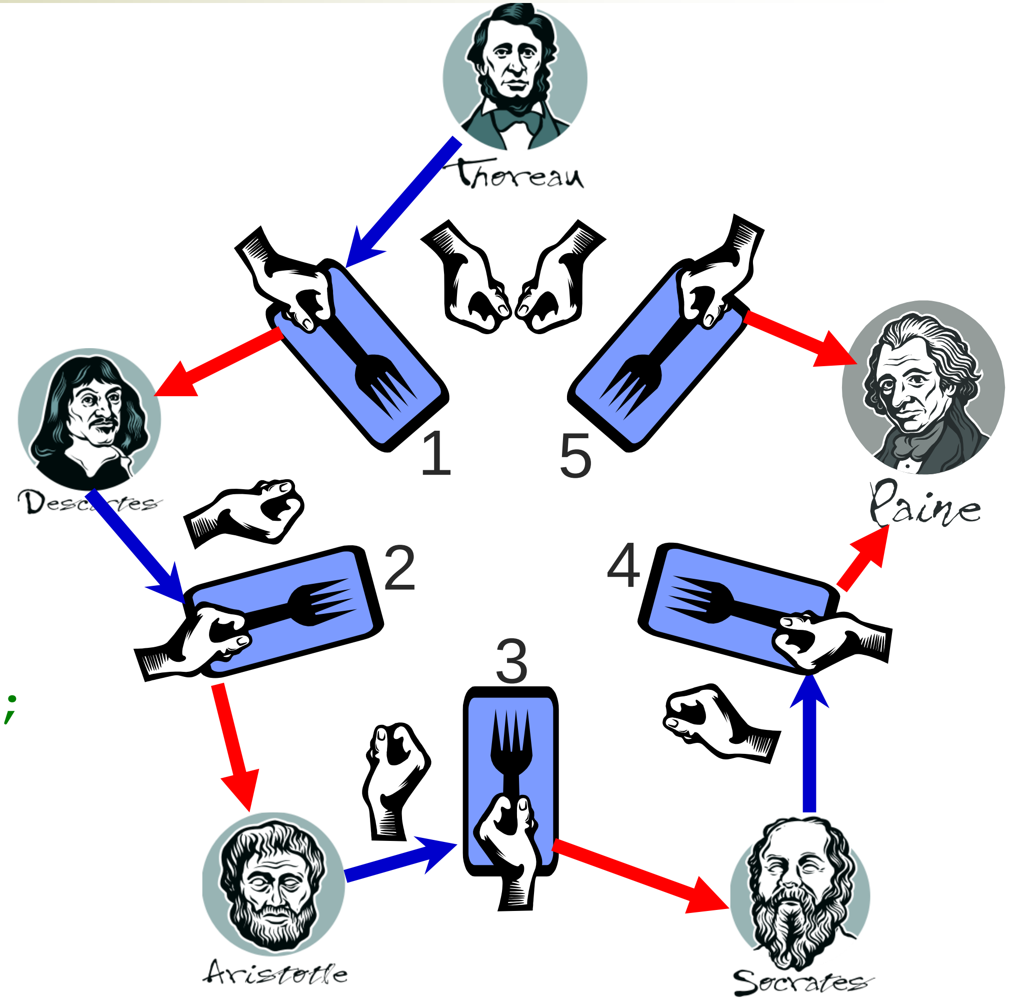
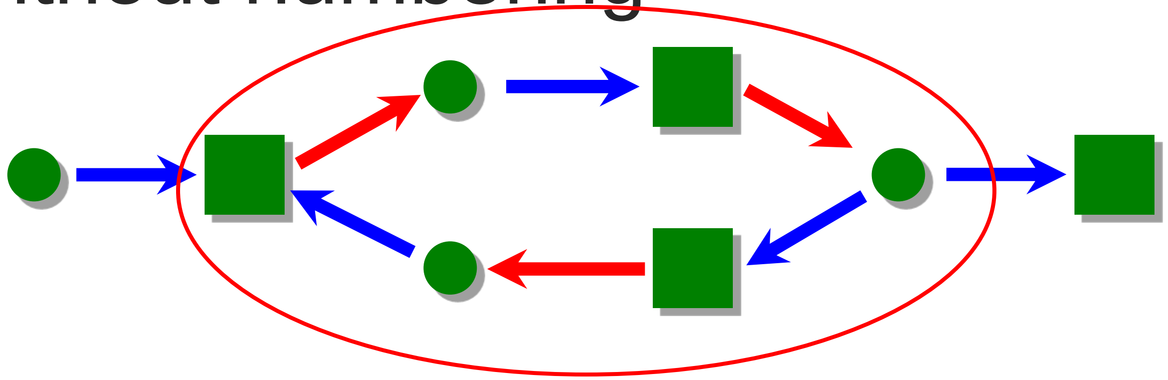


Ordered resource requests prevent deadlock

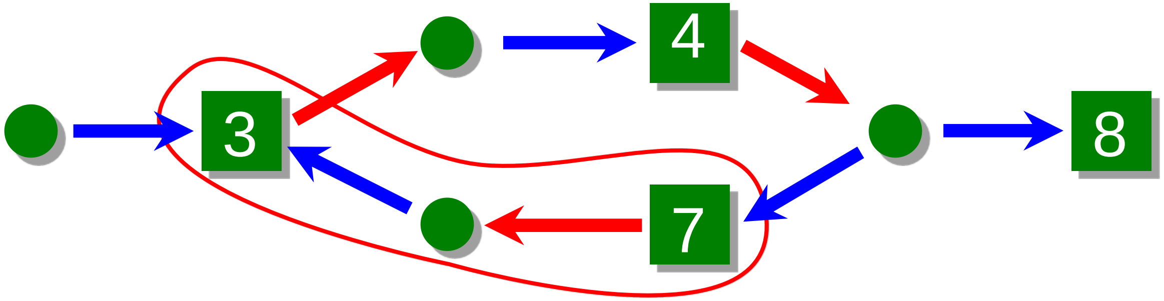
- Without numbering



Cycle!

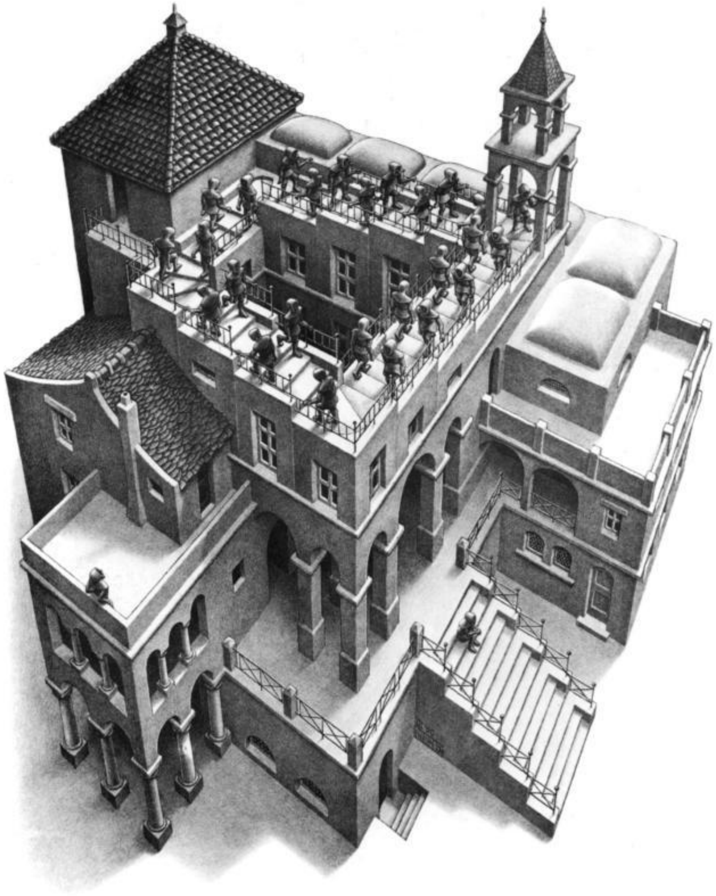
Ordered resource requests prevent deadlock

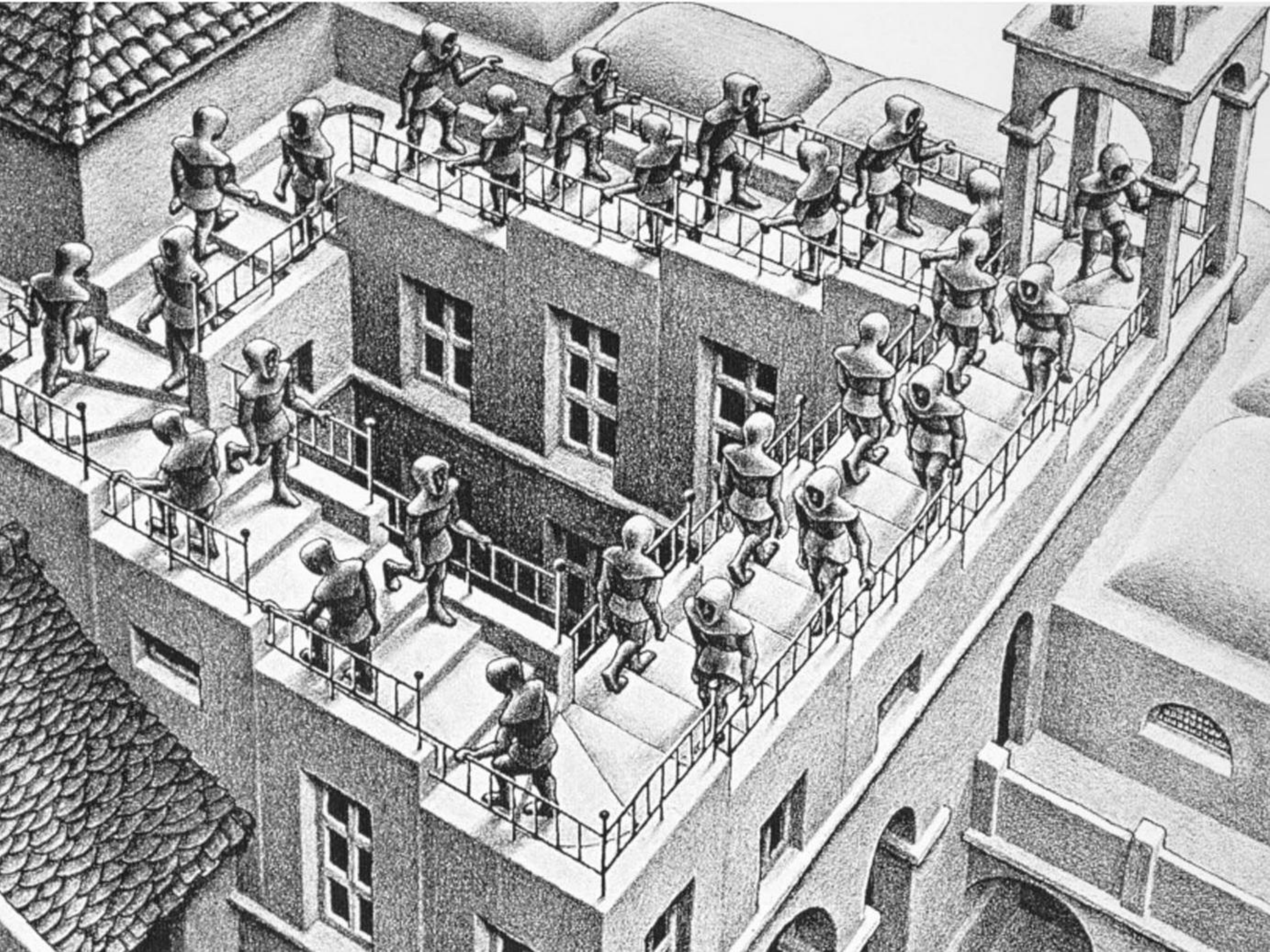
- With numbering



Contradiction:
Must have requested
3 first!

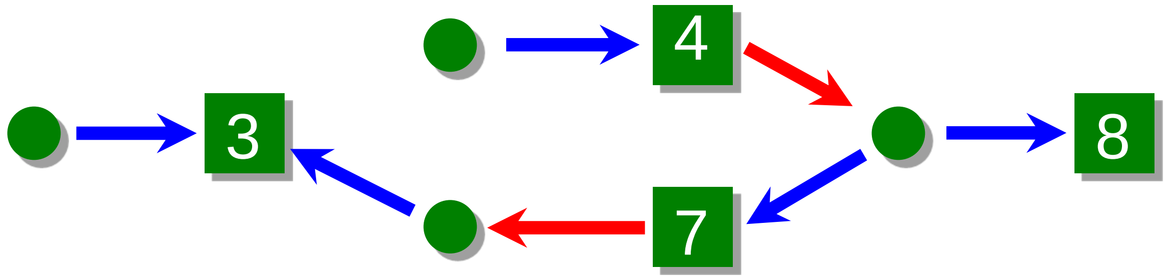
Proof by M.C. Escher





Are we always in trouble without ordering resources?

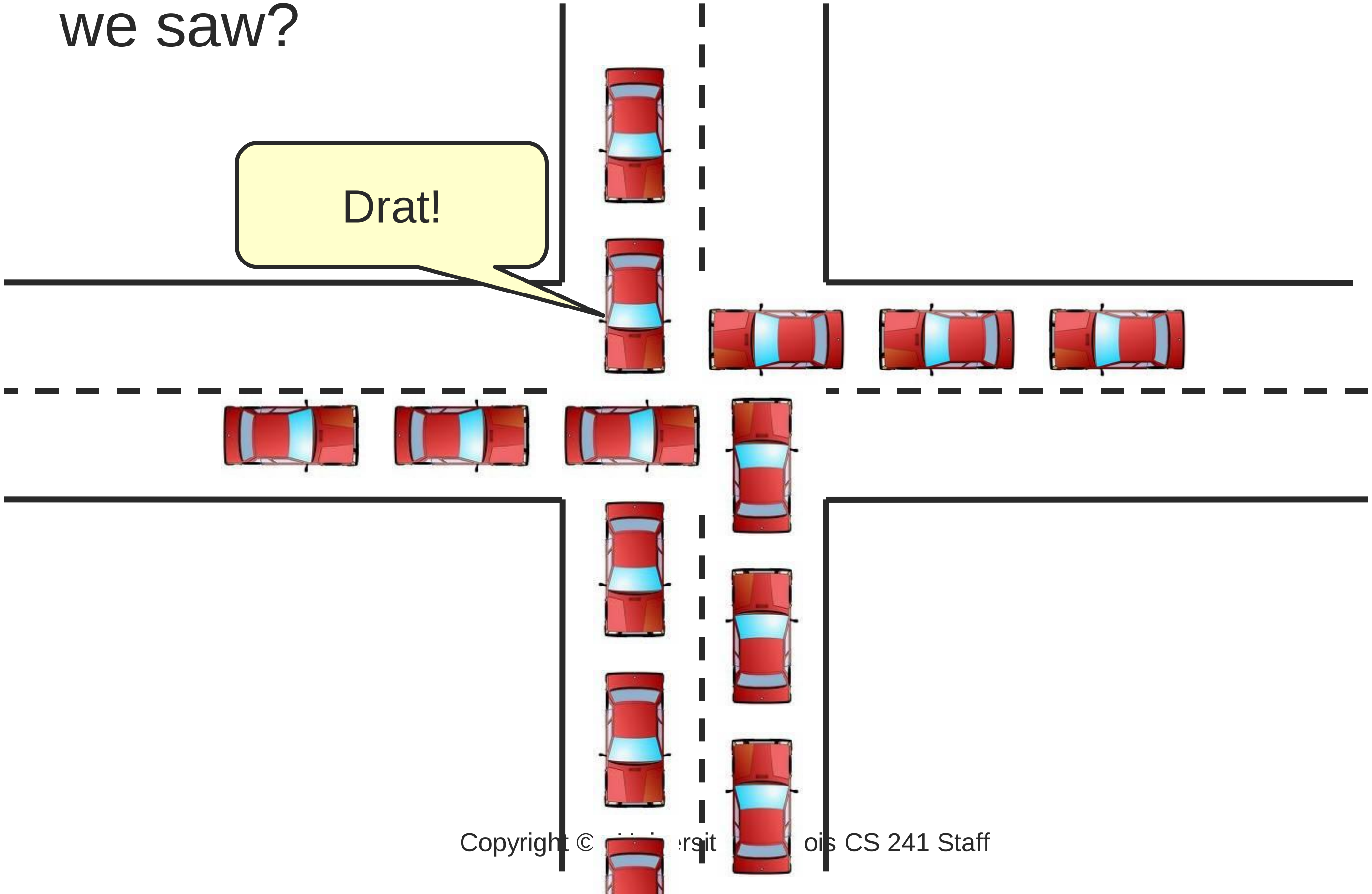
- Not always



- Ordered resource requests are sufficient to avoid deadlock, but not necessary
- Convenient, but may be conservative

Q: What’s the rule of the road?

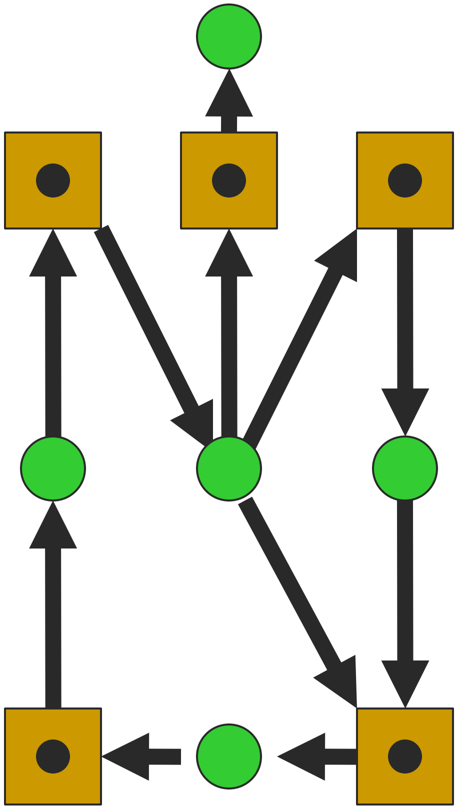
- What’s the law? Does it resemble one of the rules we saw?



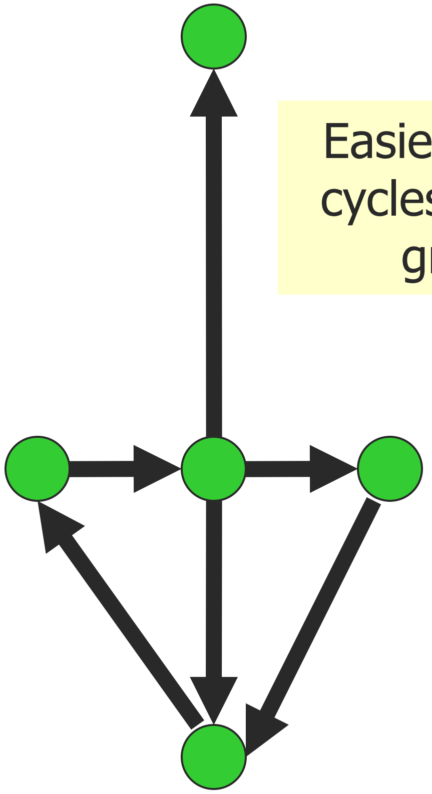
Deadlock Detection

- Check to see if a deadlock has occurred!
- Single resource per type
  - Can use wait-for graph
  - Check for cycles
    - How?

Wait for Graphs



Resource Allocation Graph

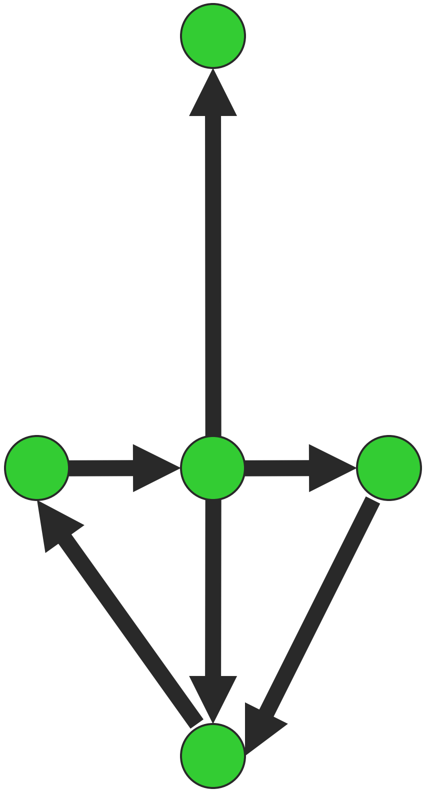


Easier to find cycles on this graph

Corresponding Wait For Graph

Deadlock Recovery

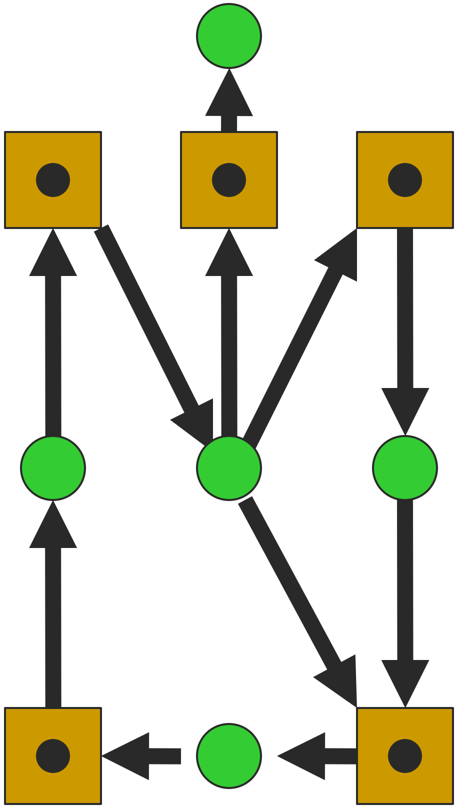
- Get rid of the cycles in the wait for graph
- How many cycles are there?



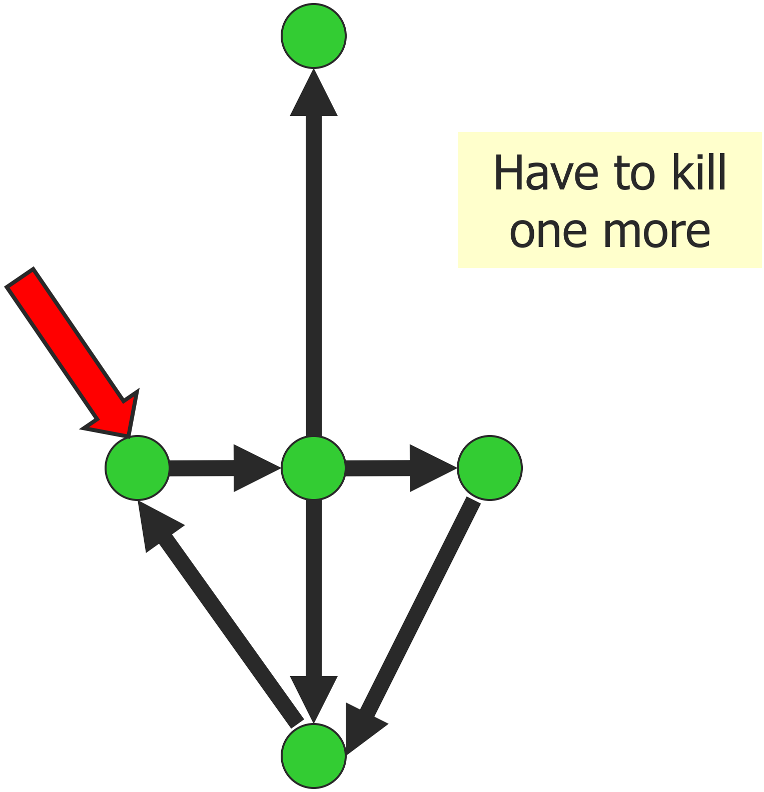
Deadlock Recovery

- Options
  - Kill all deadlocked processes and release resources
  - Kill one deadlocked process at a time and release its resources
  - Steal one resource at a time
  - Rollback all or one of the processes to a checkpoint that occurred before they requested any resources
    - Difficult to prevent indefinite postponement

Deadlock Recovery



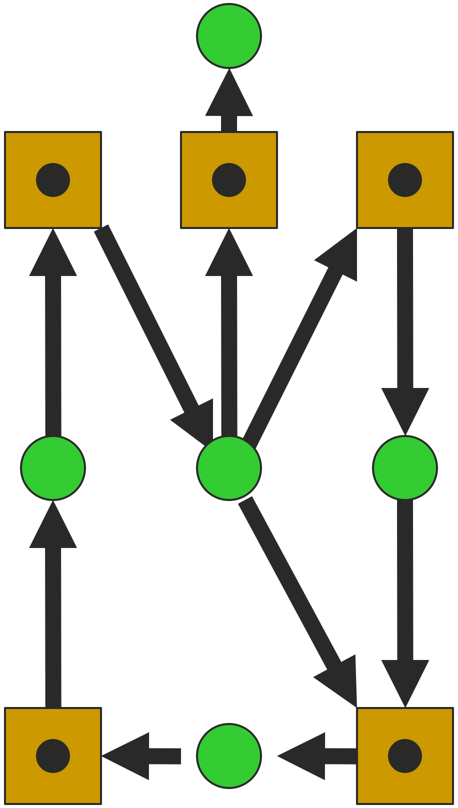
Resource
Allocation Graph



Have to kill
one more

Corresponding Wait
For Graph

Deadlock Recovery



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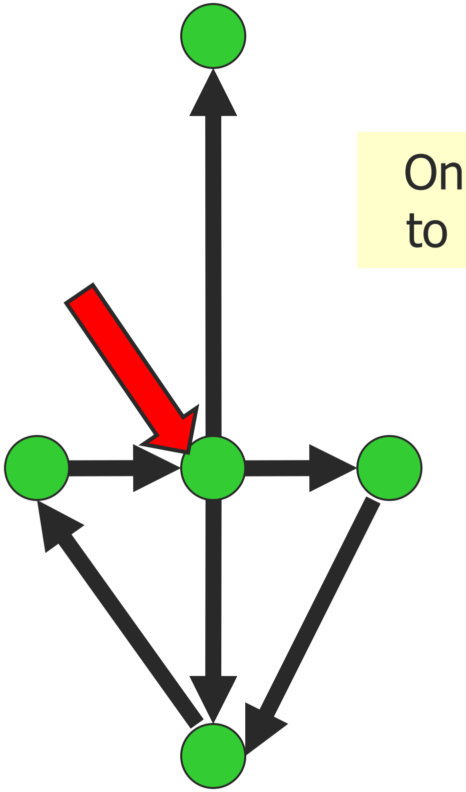

Only have
to kill one

Corresponding Wait
For Graph

Deadlock Recovery: Process Termination

- How should the aborted process be chosen?
  - Process priority
  - Current computation time and time to completion
  - Amount of resources used by the process
  - Amount of resources needed by the process to complete
  - If this process is terminated, how many other processes will need to be terminated?
  - Is process interactive or batch?

Deadlock Recovery: Resource Preemption

- Selecting a victim
  - Minimize cost
- Rollback
  - Return to some safe state
  - Restart process for that state
- Challenge: Starvation
  - Same process may always be picked as victim
  - Fix: Include number of rollbacks in cost factor

Deadlock Avoidance

- Basic idea
  - Resource manager tries to see the worst case that could happen
  - It does not grant an incremental resource request to a process if this allocation might lead to deadlock

Deadlock Avoidance

- Approach
  - Define a model of system states (SAFE, UNSAFE)
  - Choose a strategy that guarantees that the system will not go to a deadlock state
- Multiple instance of each Resources
  - Requires the maximum number of each resource needed for each process
    - For each resource **`i`**, **`p.Max[i]`** = maximum number of instances of **`i`** that **`p`** can request

Safe vs. Unsafe

- Safe
  - Guarantee
    - There is some scheduling order in which every process can run to completion even if all of them suddenly and simultaneously request their maximum number of resources
  - From a safe state
    - The system can guarantee that all processes will finish
- Unsafe state: no such guarantee
  - A deadlock state is an unsafe state
  - An unsafe state may not be a deadlock state
  - Some process may be able to complete
- Overall
  - a conservative/pessimistic approach

How to Compute Safety

- Banker's Algorithm (Dijkstra, 1965)
  - Each customer tells banker the maximum number of resources it needs, before it starts
  - Customer borrows resources from banker
  - Customer returns resources to banker
  - Banker only lends resources if the system will stay in a safe state after the loan