Distributed 2PC & Deadlock

COMMITMENT:
EITHER YOU DO OR YOU DON'T, THERE IS NO IN-BETWEEN.

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CS162 – Operating Systems and Systems Programming

Lecture 36

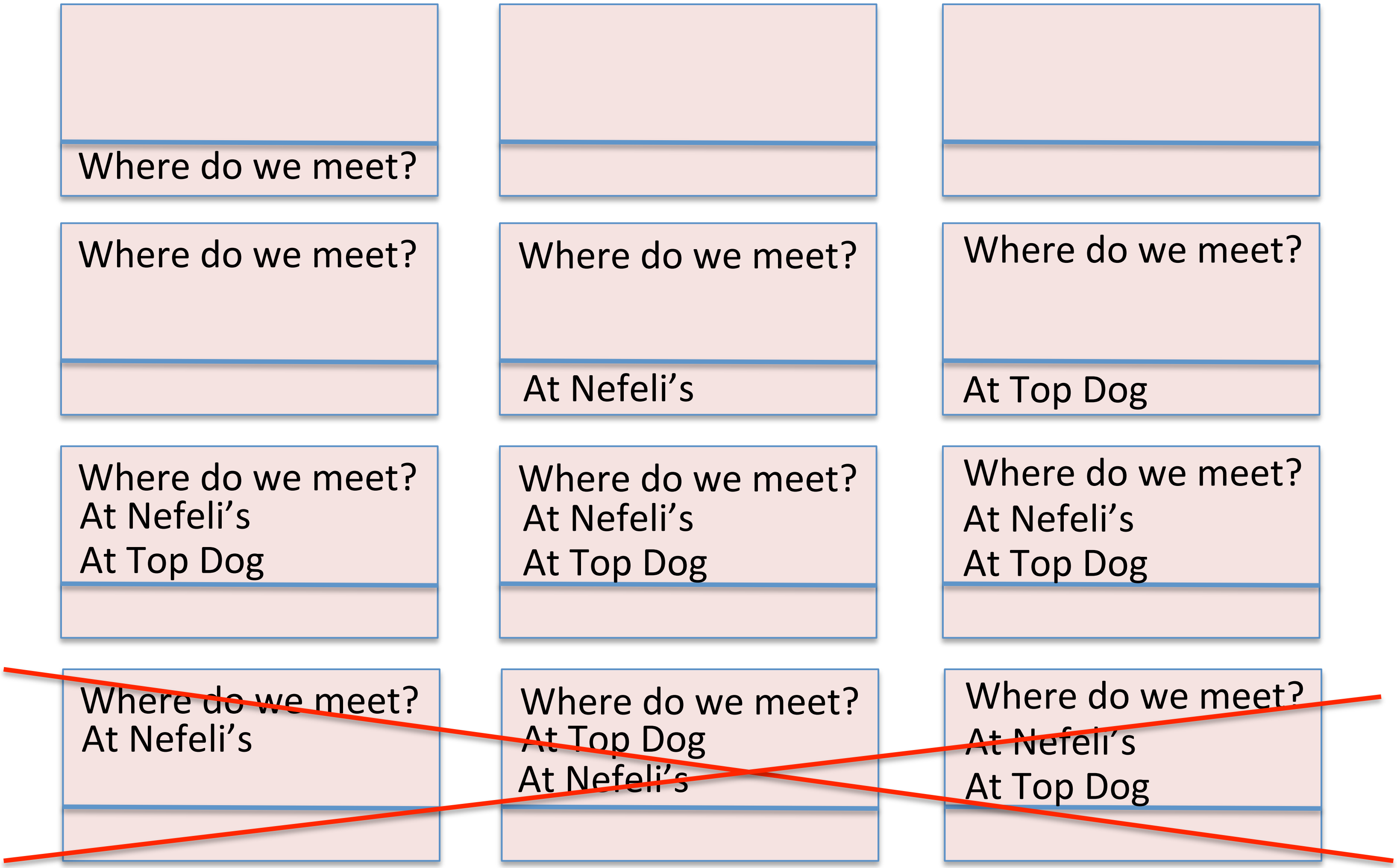
Nov 21, 2014

Reading: OSC Ch 7 (deadlock)

Consistency Review

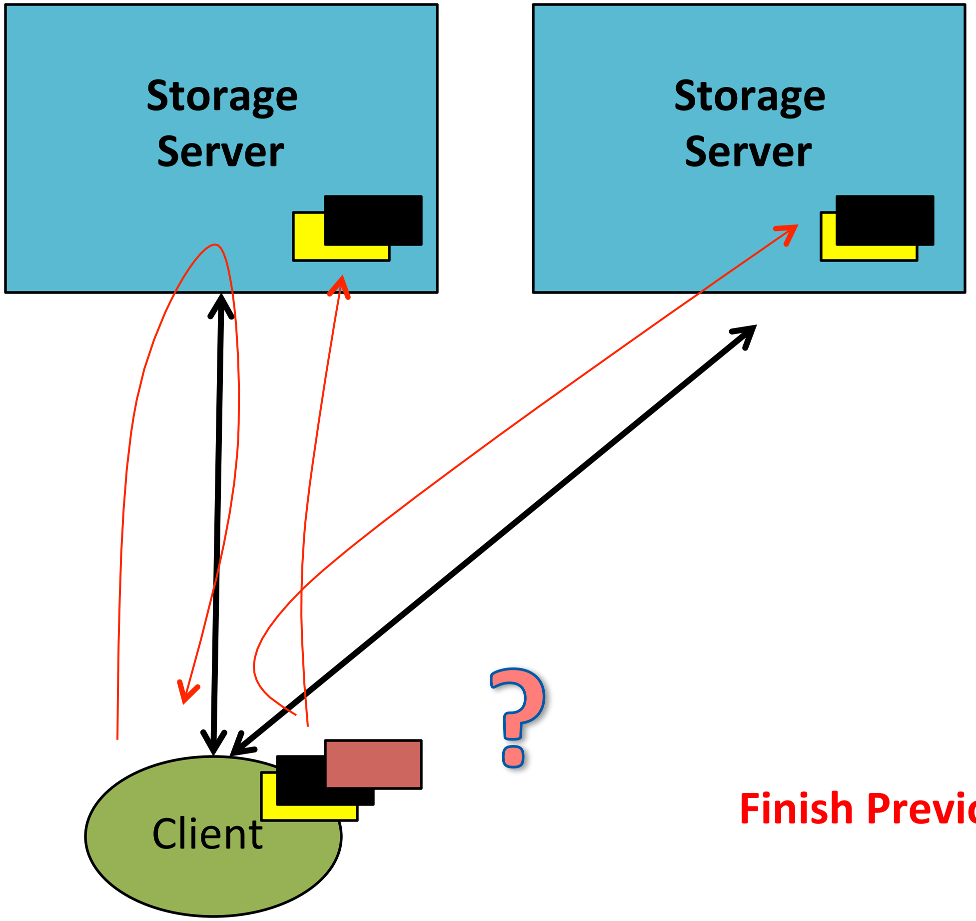
- Problem: shared state replicated across multiple clients, do they see a consistent view?
  – Propagation: Writes become visible to reads
  – Serializability: The order of writes seen by each client's series of reads and writes is *consistent* with a total order
    - As if all writes and reads had been serviced at a single point
    - The total order is not actually generated, but it could be
- Many distributed systems provide weaker semantics
  – Eventual consistency

In Everyday Life



- Alternative: timestamp every write, present entire log in timestamp order, with tie breaker

Unfinished Business: Multiple Servers



Finish Previous Lecture

- What happens if cannot update all the replicas?
- Availability => Inconsistency

Durability and Atomicity

- How do you make sure transaction results persist in the face of failures (e.g., server node failures)?

- Replicate store / database
  - Commit transaction to each replica

- What happens if you have failures during a transaction commit?
  - Need to ensure atomicity: either transaction is committed on all replicas or none at all

Two Phase (2PC) Commit

- 2PC is a distributed protocol
- High-level problem statement
  - If no node fails and all nodes are ready to commit, then all nodes **COMMIT**
  - Otherwise **ABORT** at all nodes
- Developed by Turing award winner Jim Gray (first Berkeley CS PhD, 1969)

2PC Algorithm

- One coordinator
- N workers (replicas)

- High level algorithm description
  - Coordinator asks all workers if they can commit
  - If all workers reply "VOTE-COMMIT", then coordinator broadcasts "GLOBAL-COMMIT",

    Otherwise coordinator broadcasts "GLOBAL-ABORT"
  - Workers obey the GLOBAL messages

Detailed Algorithm

Coordinator Algorithm

Coordinator sends VOTE-REQ to all workers

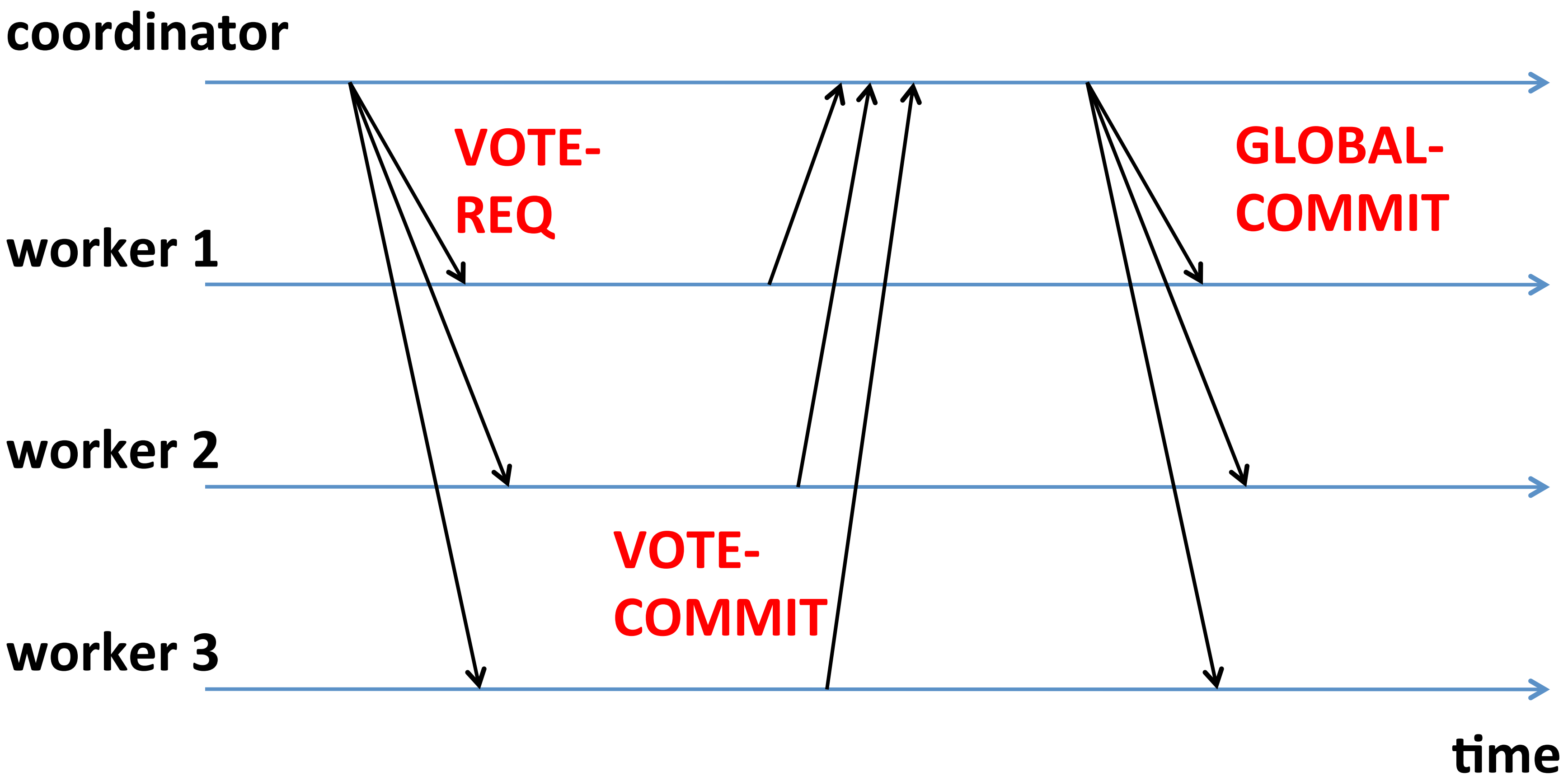
- If receive VOTE-COMMIT from all N workers, send GLOBAL-COMMIT to all workers
- If doesn't receive VOTE-COMMIT from all N workers, send GLOBAL-ABORT to all workers

Worker Algorithm

- Wait for VOTE-REQ from coordinator
- If ready, send VOTE-COMMIT to coordinator
- If not ready, send VOTE-ABORT to coordinator
  - And immediately abort

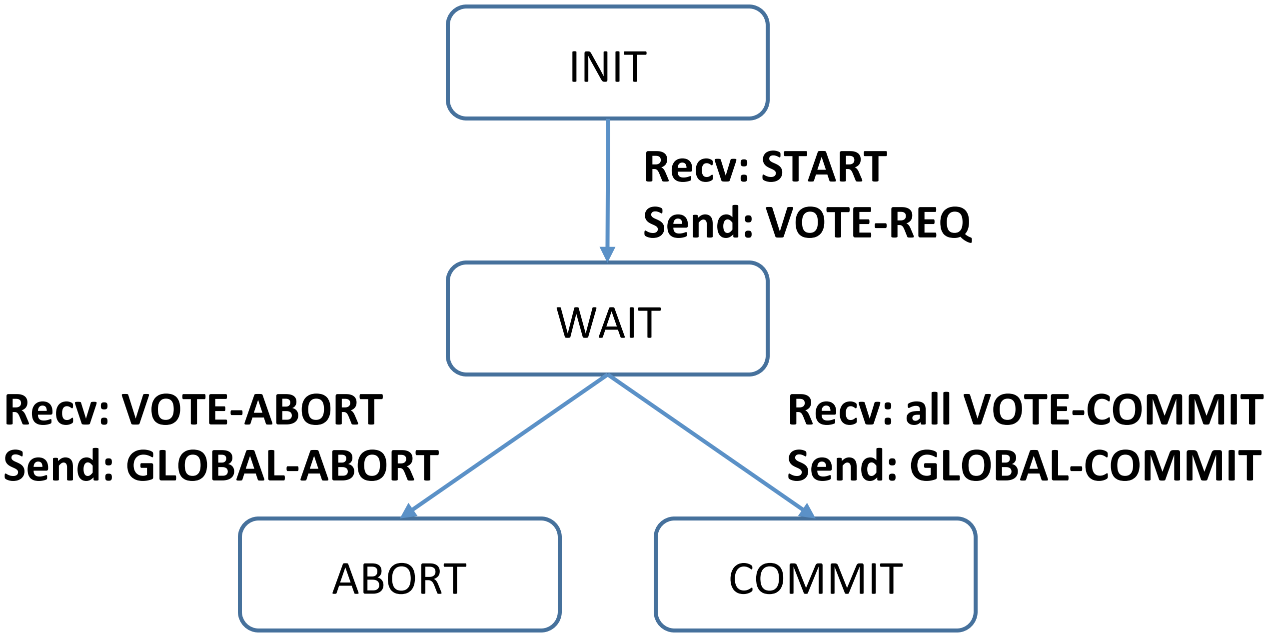
- If receive GLOBAL-COMMIT then commit
- If receive GLOBAL-ABORT then abort

Failure Free Example Execution

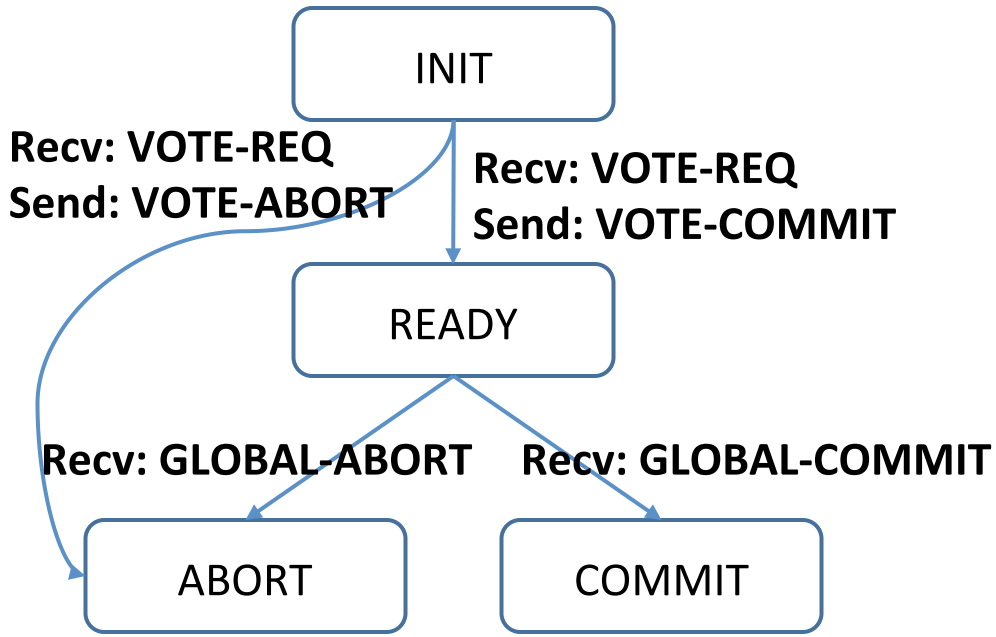


State Machine of Coordinator

- Coordinator implements simple state machine

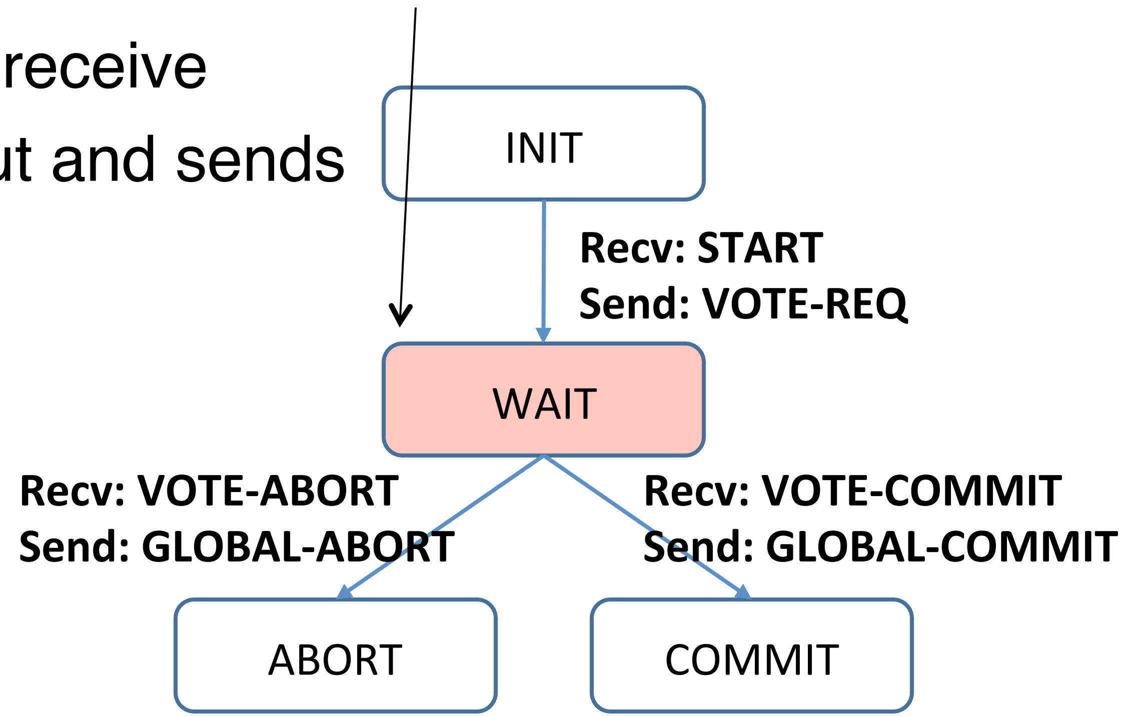


State Machine of Workers

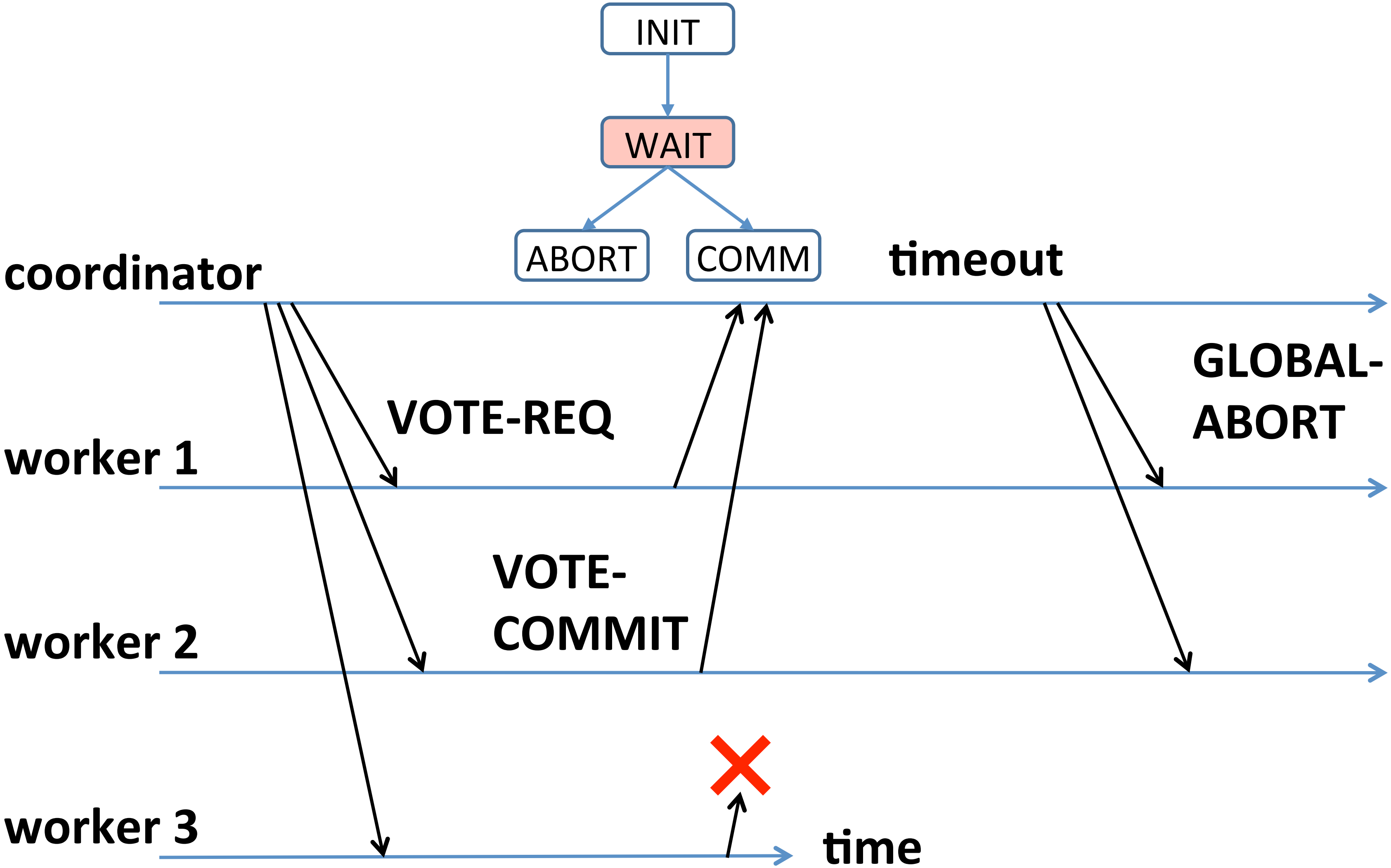


Dealing with Worker Failures

- How to deal with worker failures?
  - Failure only affects states in which the node is waiting for messages
  - Coordinator only waits for votes in "WAIT" state
  - In WAIT, if doesn't receive N votes, it times out and sends GLOBAL-ABORT

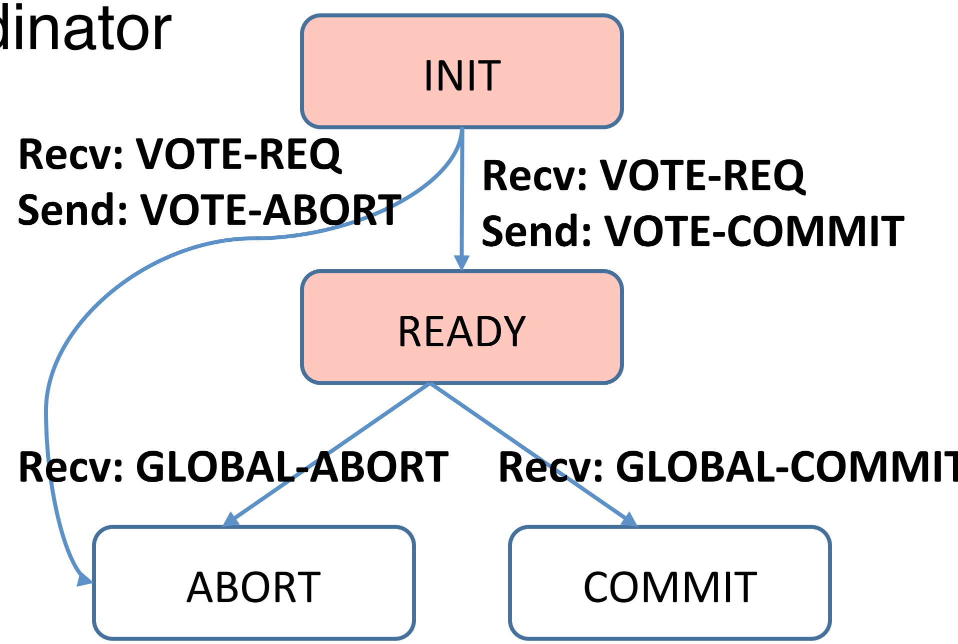


Example of Worker Failure

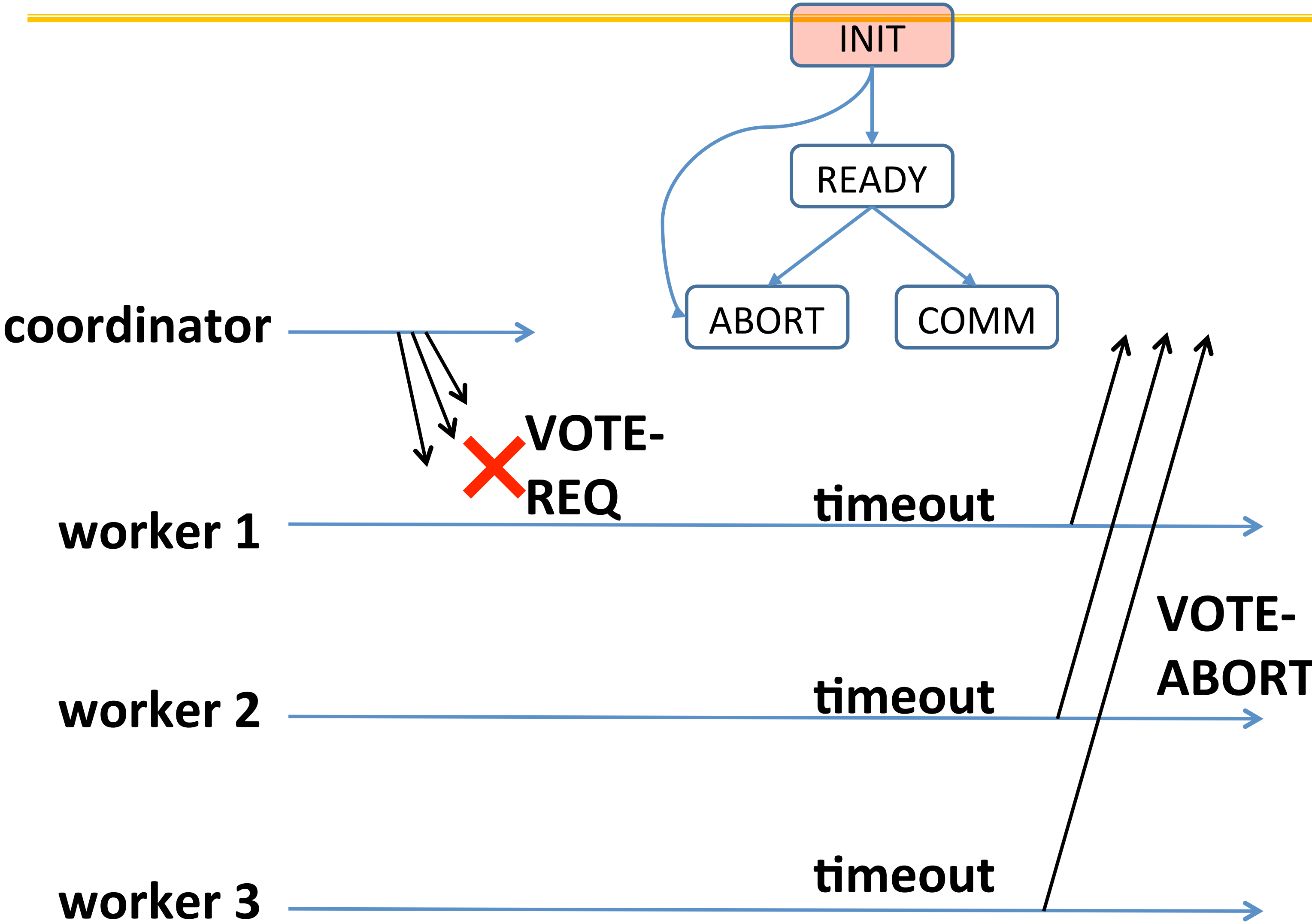


Dealing with Coordinator Failure

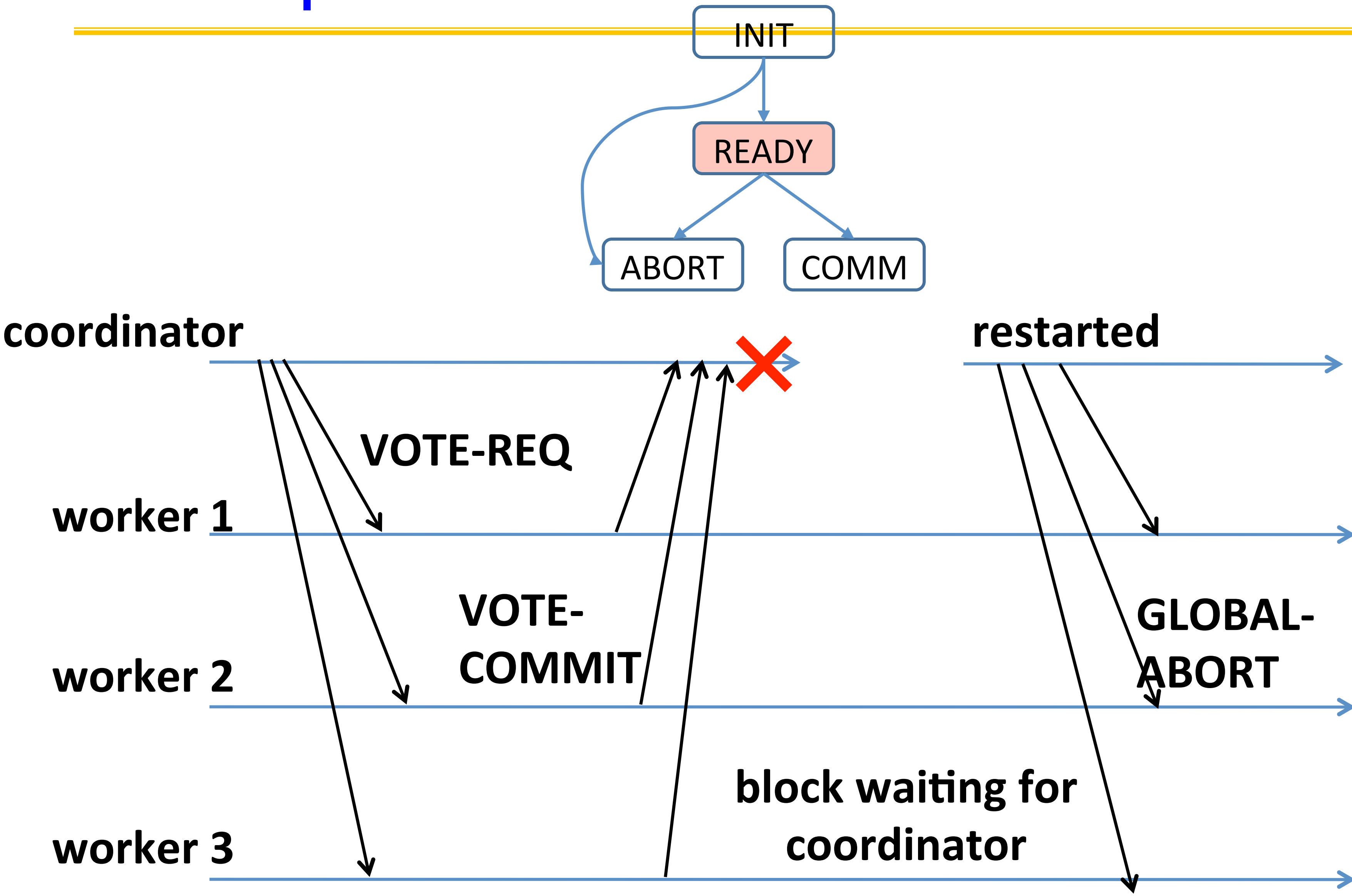
- How to deal with coordinator failures?
  - worker waits for VOTE-REQ in INIT
    - Worker can time out and abort (coordinator handles it)
  - worker waits for GLOBAL-* message in READY
    - If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send GLOBAL_* message



Example of Coordinator Failure #1



Example of Coordinator Failure #2



Durability

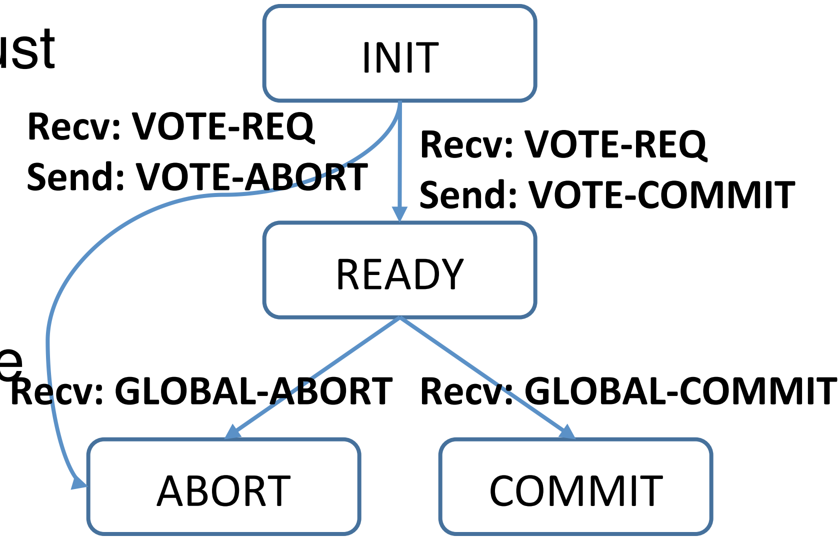
- All nodes use stable storage* to store which state they are in

- Upon recovery, it can restore state and resume:
  - Coordinator aborts in INIT, WAIT, or ABORT
  - Coordinator commits in COMMIT
  - Worker aborts in INIT, ABORT
  - Worker commits in COMMIT
  - Worker asks Coordinator in READY

* - stable storage is non-volatile storage (e.g. backed by disk) that guarantees atomic writes.

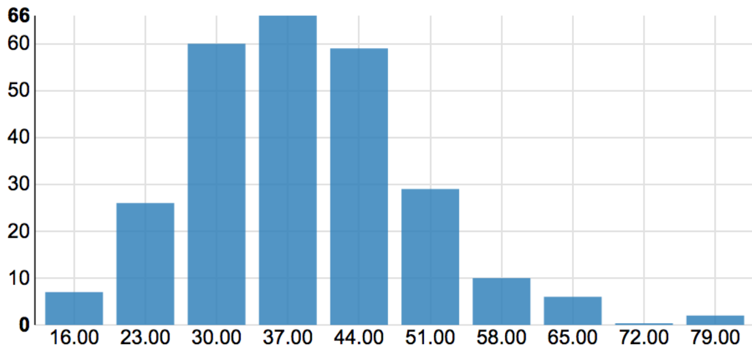
Blocking for Coordinator to Recover

- A worker waiting for global decision can ask fellow workers about their state
  - If another worker is in ABORT or COMMIT state then coordinator must have sent GLOBAL-*
  - Thus, worker can safely abort or commit, respectively
  - If another worker is still in INIT state then both workers can decide to abort
  - If all workers are in ready, need to **BLOCK** (don't know if coordinator wanted to abort or commit)

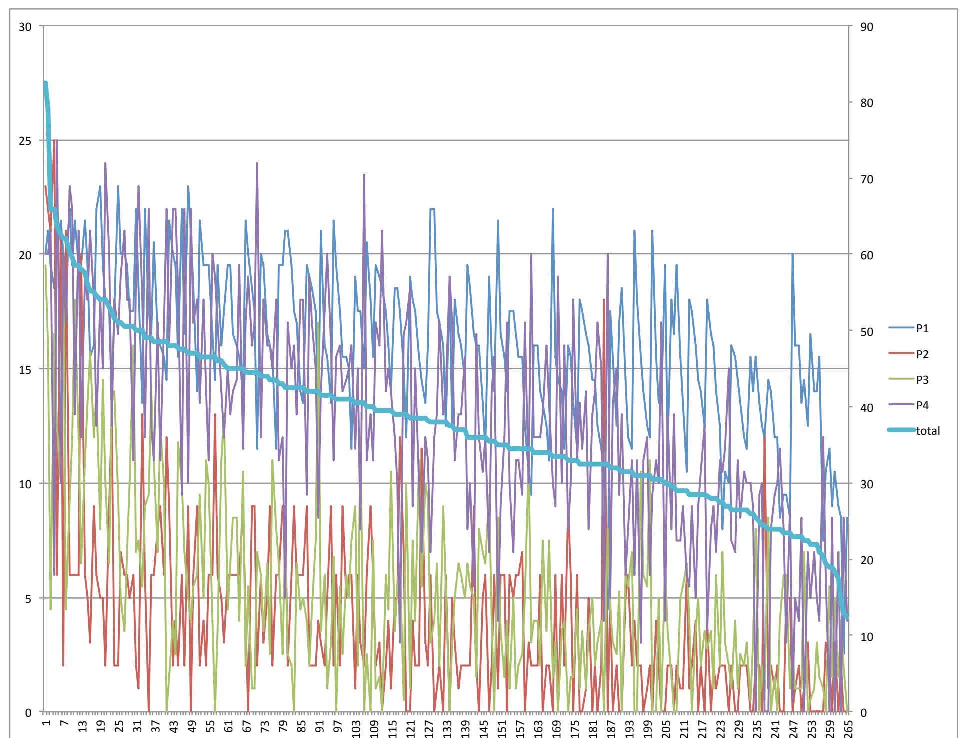


Admin Break

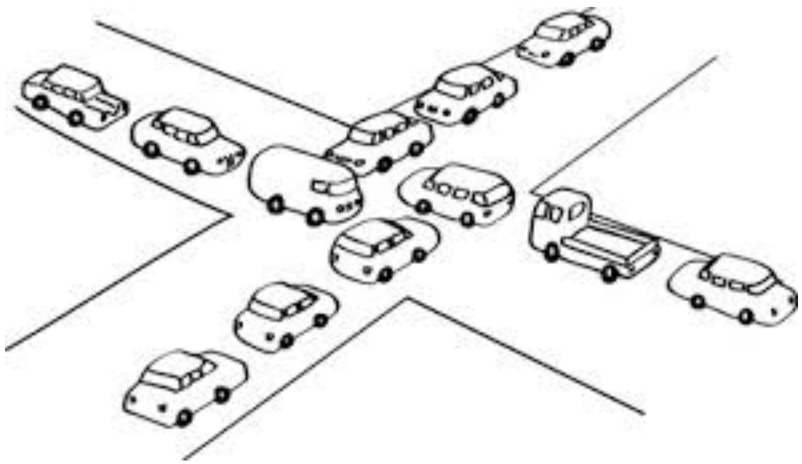
- MidTerm (mult by 4/3)



12.5	82.5	38.03	38.0	10.87
MIN	MAX	MEAN	MEDIAN	STD DEV

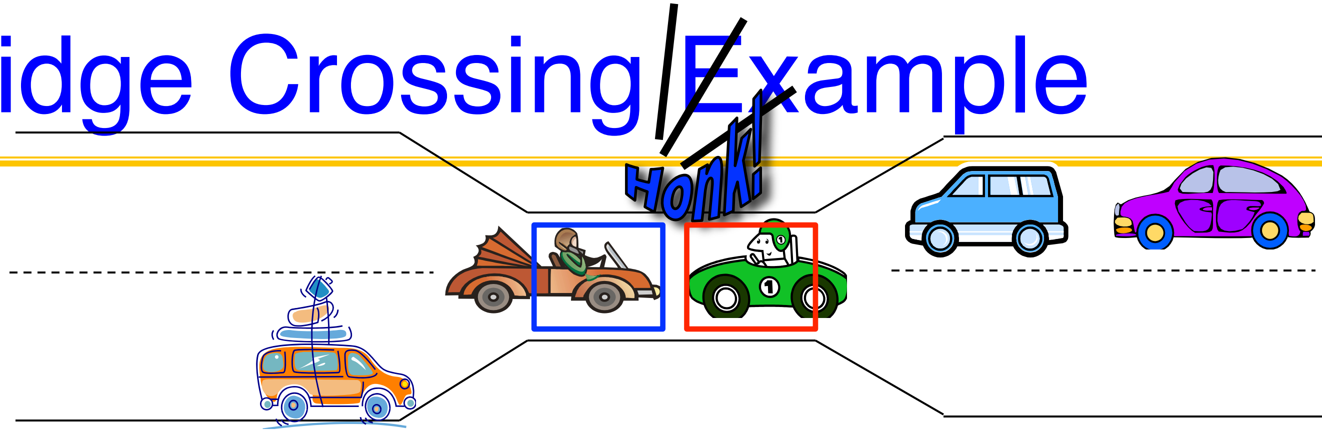


What's a Deadlock?



- Situation where all entities (e.g., threads, clients, …)
  - have acquired certain resources and
  - need to acquire additional resources,
  - but those additional resources are held some other entity that won't release them

Bridge Crossing Example



- Each segment of road can be viewed as a resource
  - Car "owns" the segment under them
  - Must acquire segment that they are moving into
- Must acquire both halves of bridge to cross
  - Traffic only in one direction at a time
  - Problem occurs when two cars in opposite directions on bridge: each acquires one segment and needs next
- 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
  - East-going traffic really fast ⇒ no one goes west

OS analog of the bridge

- Exclusive Access to Multiple Resouces:

```
x=1, y=1
            Thread A              Thread B
            x.Down();             y.Down();
            y.Down();             x.Down();
              …                     …
             y.Up();               x.Up();
            x.Up();               y.Up();
```

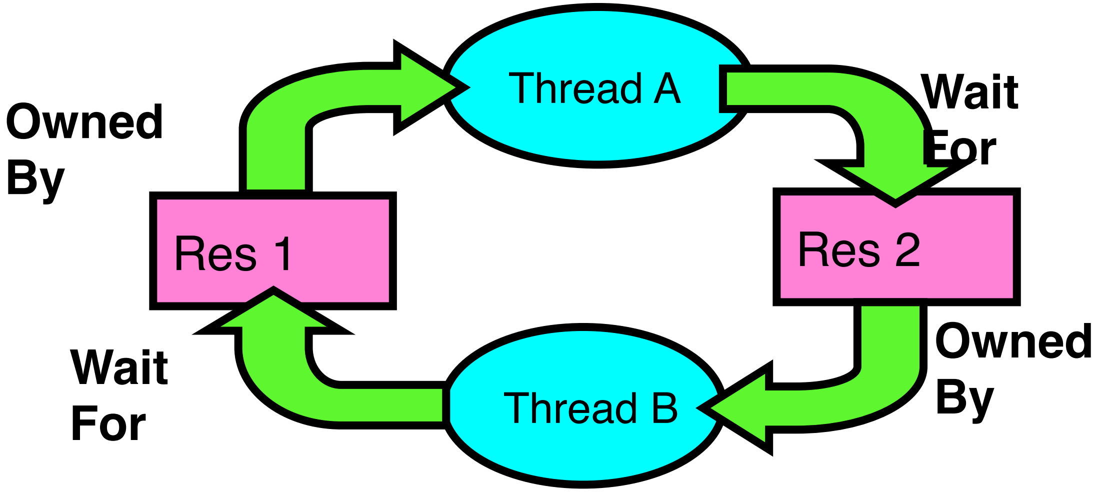
Deadlock

```
A:  x.Down();
B:  y.Down();
A:  y.Down();
B:  x.Down();
...
```

- **Say, x is free-list and y is directory**

Deadlock vs. Starvation

- Deadlock: circular waiting for resources
  - Thread A owns Res 1 and is waiting for Res 2
    Thread B owns Res 2 and is waiting for Res 1



- Starvation: thread waits indefinitely
  - Example, low-priority thread waiting for resources constantly in use by high-priority threads
- Deadlock ⇒ Starvation, but not vice versa
  - Starvation can end (but doesn't have to)
  - Deadlock can't end without external intervention

OS analog of the bridge

- Exclusive Access to Multiple Resouces:

```
x=1, y=1
        Thread A              Thread B
        x.Down();             y.Down();
        y.Down();             x.Down();
         …                    …
         y.Up();               x.Up();
         x.Up();               y.Up();
```

Deadlock

```
A:  x.Down();
B:  y.Down();
A:  y.Down();
B:  x.Down();
...
```

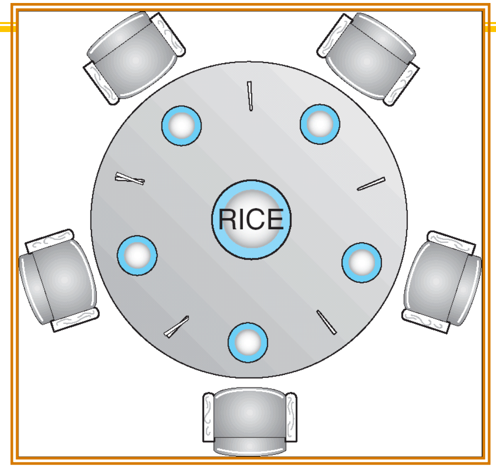
- **Say, x is free-list and y is directory structure**
- **Deadlock is typically not deterministic**
  - **Timing in this example has to be "just so"**
- Deadlocks occur with multiple resources
  - Can't solve deadlock for each resource independently

Can this deadlock?

```
void transaction(account *from, account *to, double amount)
{
    acquire(from->lock);
    acquire(to->lock);
    withdraw(from, amount);
    deposit(to, amount);
    release(from->lock);
    release(to->lock);
}
```

- Under what conditions?

Dining Philosophers Problem

- N chopsticks/ N philosophers
  - Need two chopsticks to eat
  - Free for all: Philosopher will grab any one they can
- What if all grab at same time?
  - Deadlock!
- How to fix deadlock?
  - Make one of them give up a chopstick (Hah!)
  - Eventually everyone will get chance to eat
- How to prevent deadlock?

Four requirements for Deadlock

- Mutual exclusion
  - Only one thread at a time can use a resource
- Hold and wait (incremental allocation)
  - Thread holding at least one resource is waiting to acquire additional resources held by other threads
- No preemption
  - Resources are released only voluntarily by the thread holding the resource, after thread is finished with it
- Circular wait
  - e.g, There exists a set $\{T_1, \ldots, T_n\}$ of waiting threads,
    - T_1 is waiting for a resource that is held by T_2
    - T_2 is waiting for a resource that is held by T_3, …
    - T_n is waiting for a resource that is held by T_1

Methods for Handling Deadlocks

- Deadlock prevention: design system to ensure that it will *never* enter a deadlock
  - E.g., monitor all lock acquisitions
  - Selectively deny those that *might* lead to deadlock
- Allow system to enter deadlock and then recover
  - Requires deadlock detection algorithm
    - E.g., Java JMX findDeadlockedThreads()
  - Some technique for forcibly preempting resources and/or terminating tasks
- Ignore the problem and hope that deadlocks never occur in the system
  - Used by most operating systems, including UNIX
  - Resort to manual version of recovery

Techniques for Deadlock Prevention

- Eliminate the Shared Resources
  - E.g., give each Philosopher two chopsticks, open the other bridge lane, …
  - Or at least two virtual chopsticks
  - OK, if sharing was do to resource limitations
  - Not if sharing is due to true interactions
    - Must modify Directory Structure AND File Index AND the Block Free list
    - Must enter the intersection to turn left

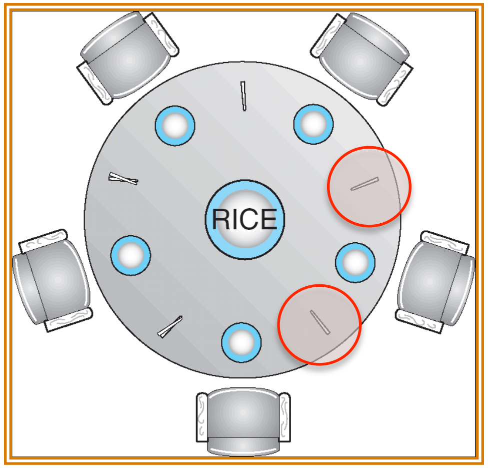
Techniques for Deadlock Prevention

- Eliminate the Shared Resources
- Eliminate the Mutual Exclusion
  - E.g., many processes can have read-only access to file
  - But still need mutual-exclusion for writing

Techniques for Deadlock Prevention

- Eliminate the Shared Resources
- Eliminate the Mutual Exclusion
- Eliminate Hold-and-Wait

Acquire all resources up front

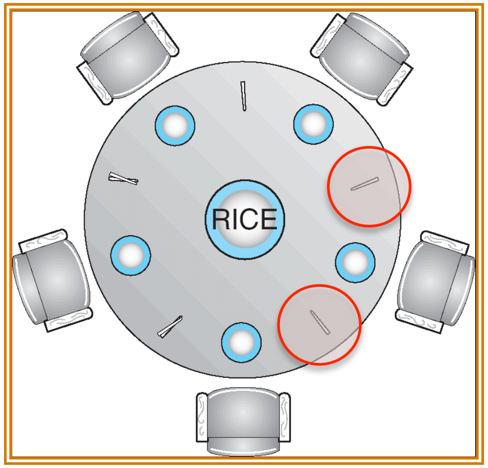


- Philosopher grabs for both chopsticks at once
  - If not both available, don't pickup either, try again later
- Phone call signaling attempts to acquire resources all along the path, "busy" if any point not available
- File Systems: lock {dir. Structure, file index, free list}
  - Or the piece of each in a common block group
- Databases: lock all tables touched by the query
- Hard in general, but often natural in specific cases

Techniques for Deadlock Prevention

- Eliminate the Shared Resources
- Eliminate the Mutual Exclusion
- Eliminate Hold-and-Wait
- Permit pre-emption

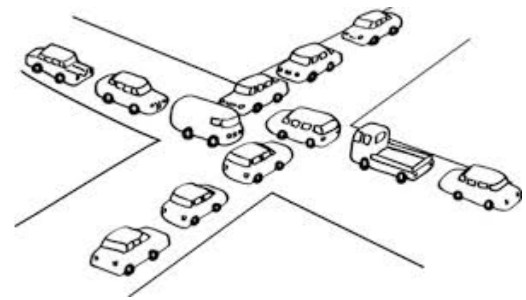
Incremental Acquisition with Pre-emption

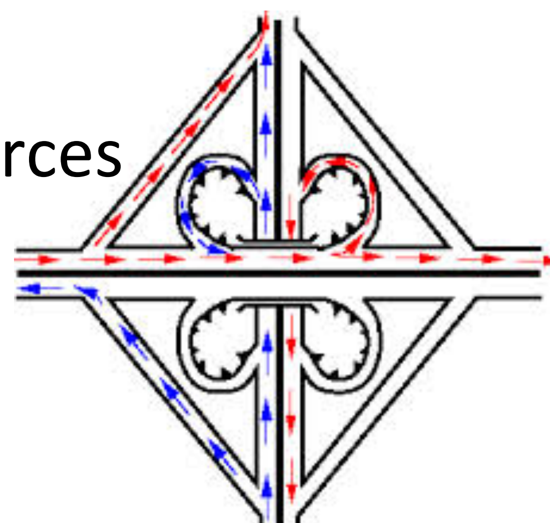


- Philosopher grabs one, goes for other, if not available, releases the first
  – Analogous for sequence of system resources
- Danger of turning deadlock into livelock
  – Everyone is grabbing and releasing, no one every gets two
- Works great at low utilization
  – Potential for thrashing (or failure) as utilization increases
- Similar to CSMA (carrier sense multiple access) in networks
- Randomize the back-off

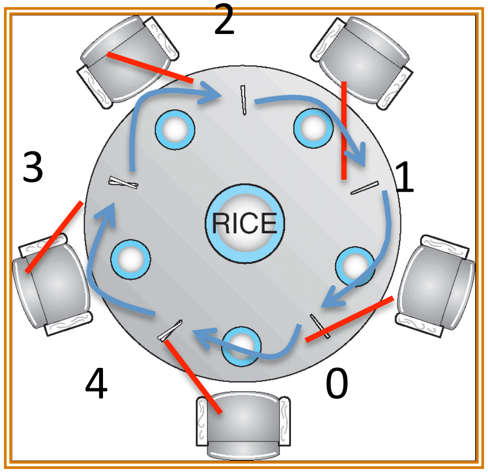
Techniques for Deadlock Prevention

- Eliminate the Shared Resources
- Eliminate the Mutual Exclusion
- Eliminate Hold-and-Wait
- Permit pre-emption
- Eliminate the creation of circular wait
  - Dedicated resources to break cycles
  - Ordering on the acquisition of resources



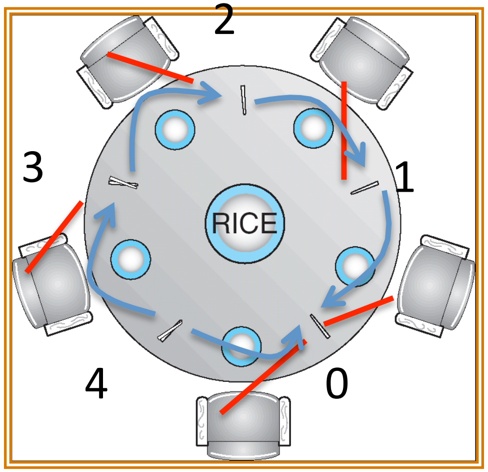


Cyclic Dependence of resources



- Suppose everyone grabs left first
- Acquisition of the right chopstick depends on the acquisition of the left one
- A cycle of dependences forms

Ordered Acquisition to prevent cycle from forming



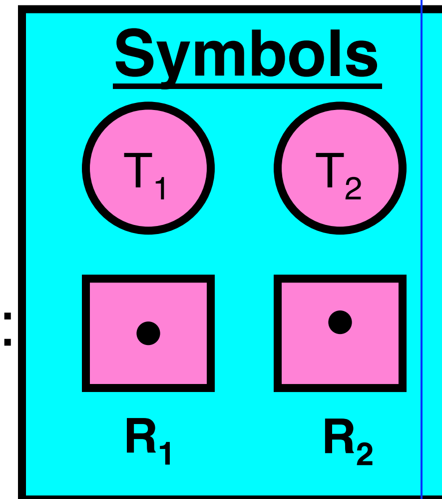
- Suppose everyone grabs lowest first
- Dependence graph is acyclic
- Someone will fail to grab chopstick 0 !
- How do you modify the rule to retain fairness ?
- OS: define ordered set of resource classes
  - Acquire locks on resources in order
  - Page Table => Memory Blocks => …

Deadlock Detection

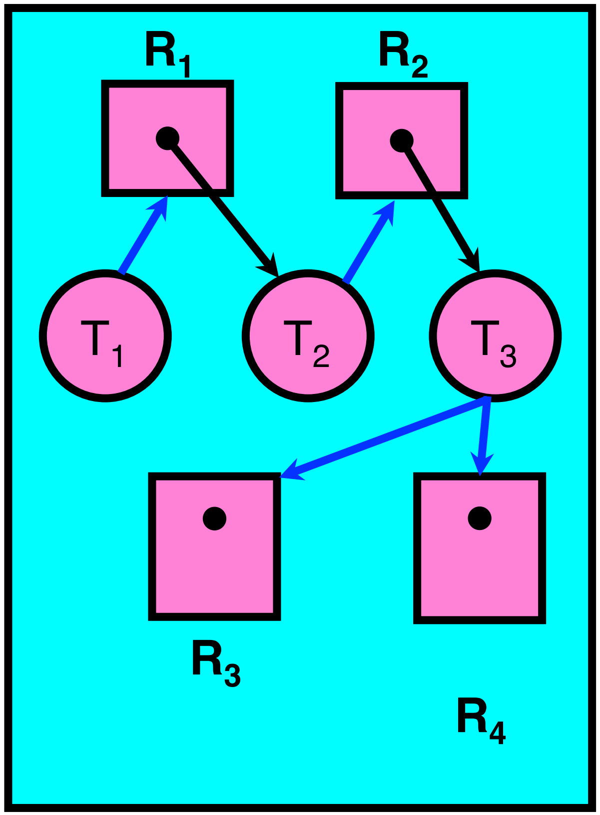
- There are threads that never become ready
- Are they deadlocked or just … ?

A Simple Resource Graph

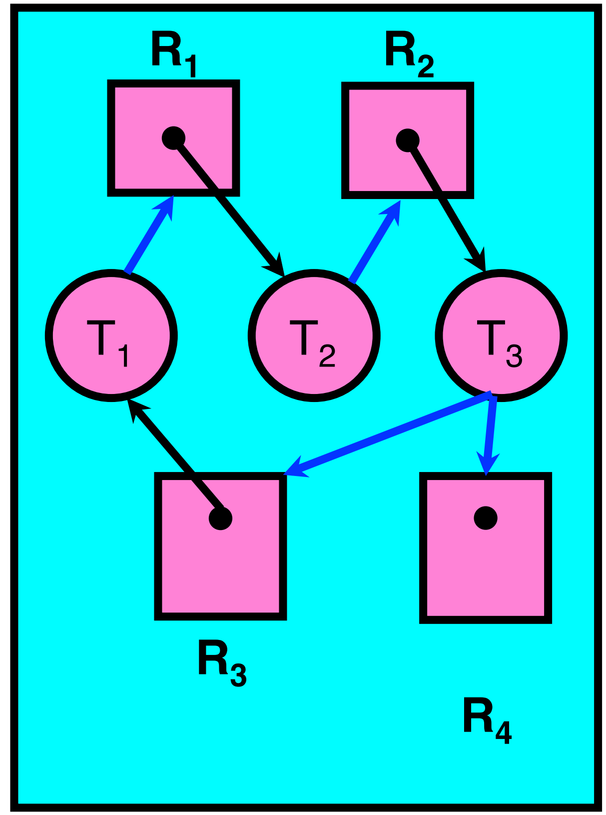
- System Model
  - A set of Threads $T_1, T_2, \ldots, T_n$
  - Resource types $R_1, R_2, \ldots, R_m$
    locks in this case
  - Each thread utilizes a resource as follows:
    - `Request() / Use() / Release()`
- Resource-Allocation Graph:
  - V is partitioned into two types:
    - $T = \{T_1, T_2, \ldots, T_n\}$, the set threads in the system.
    - $R = \{R_1, R_2, \ldots, R_m\}$, the set of resource types in system
  - request edge – directed edge $T_i \rightarrow R_j$
    - *Wait-List*
  - assignment edge – directed edge $R_j \rightarrow T_i$
    - *Owns*



Resource Allocation Graph Examples



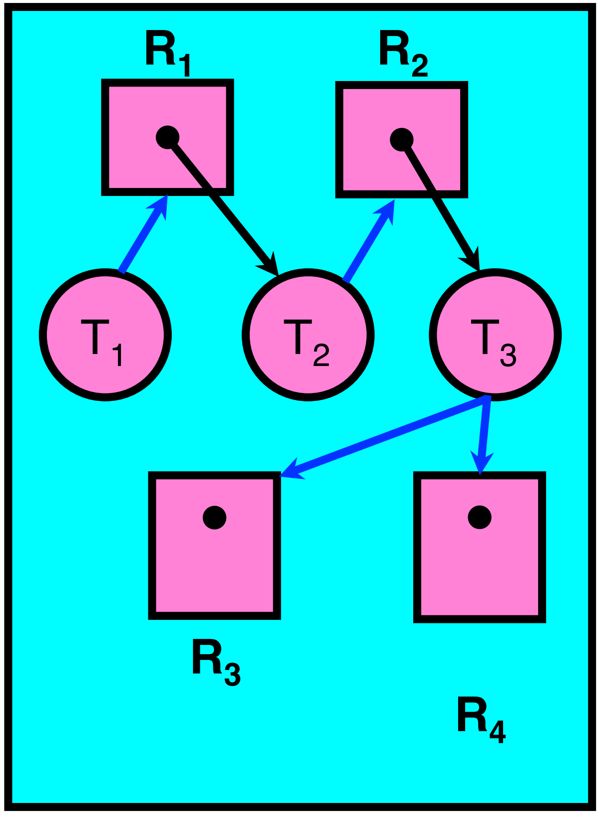
Simple Resource Allocation Graph



Deadlocked Resource Allocation Graph

How would you look for cycles?

Resource Allocation Graph Examples



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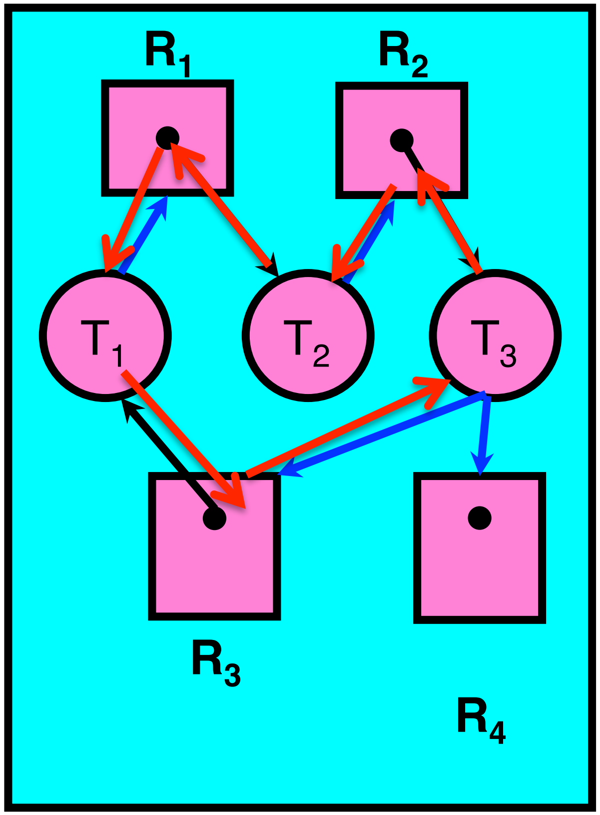
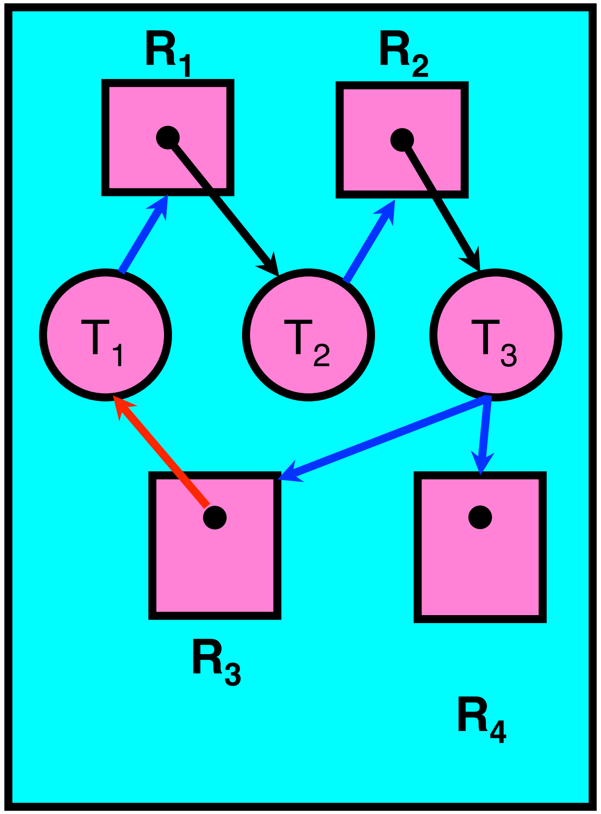


Deadlocked Resource Allocation Graph

How would avoid cycle creation ?

- On attempt to acquire an owned lock
  - Check to see if adding the request edge would create a cycle



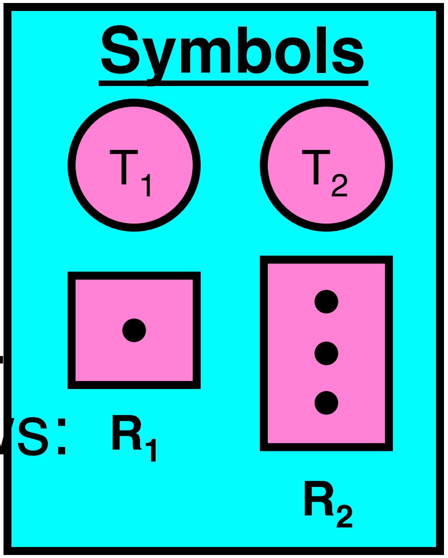
More General Case

- Each resources has a capacity (# instances)
- Each thread requests a portion of each resource

General Resource-Allocation Graph

- System Model
  - A set of Threads $T_1, T_2, \ldots, T_n$
  - Resource types $R_1, R_2, \ldots, R_m$

    CPU cycles, memory space, I/O devices
  - Each resource type R_i has W_i instances.
  - Each thread utilizes a resource as follows:
    - `Request() / Use() / Release()`



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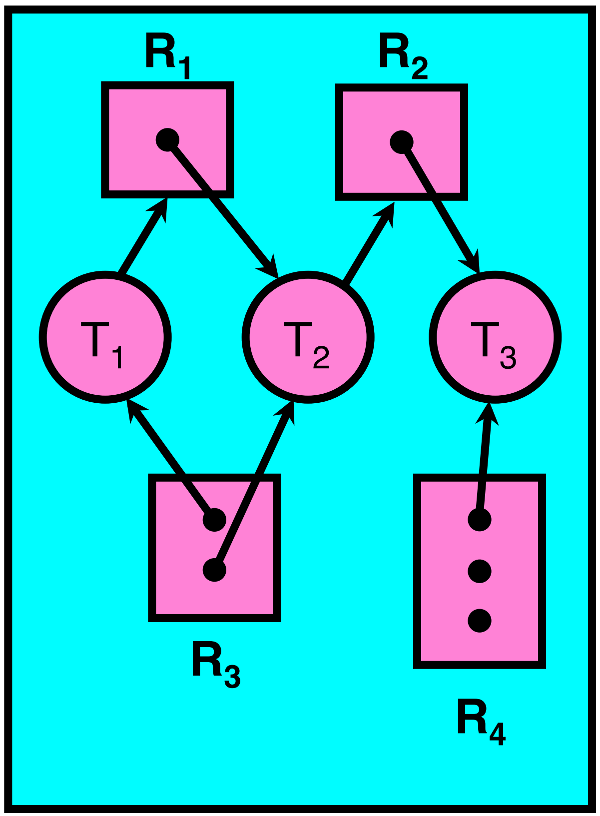
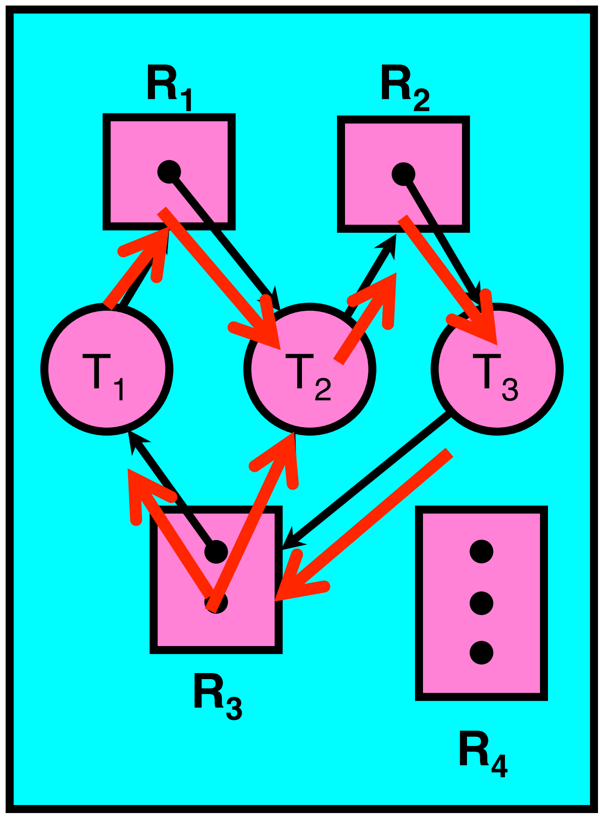
  - request edge – directed edge $T_i \rightarrow R_j$
  - assignment edge – directed edge $R_j \rightarrow T_i$

Resource Allocation Graph Examples

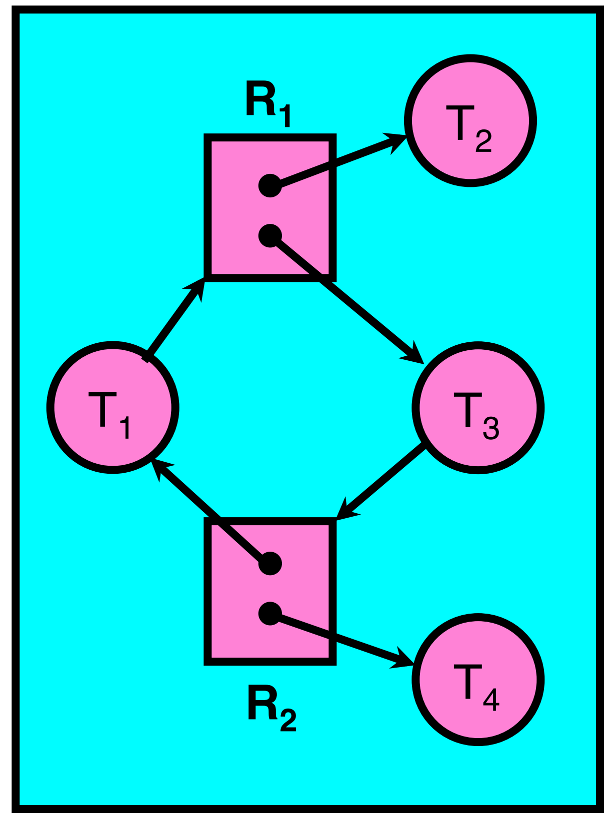
- Recall:
  - request edge – directed edge $T_i \rightarrow R_j$
  - assignment edge – directed edge $R_j \rightarrow T_i$



Simple Resource Allocation Graph



Allocation Graph With Deadlock



Allocation Graph With Cycle, but No Deadlock

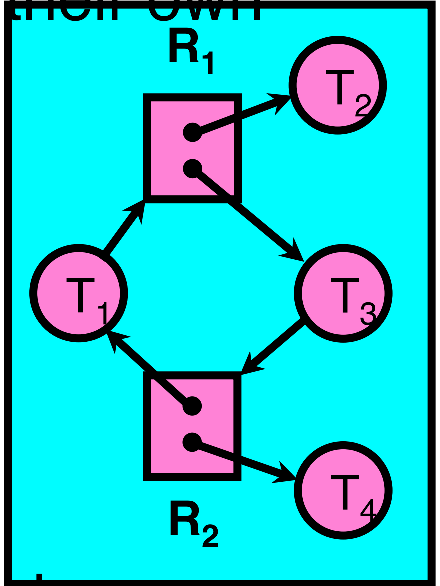
Deadlock Detection Algorithm

- Only one of each type of resource ⇒ look for loops
- More General Deadlock Detection Algorithm
  - Let [X] represent an m-ary vector of non-negative integers (quantities of resources of each type):

`[FreeResources]`:	Current free resources each type
$[Request_X]$:	Current requests from thread X
$[Alloc_X]$:	Current resources held by thread X

  - See if tasks can eventually terminate on their own

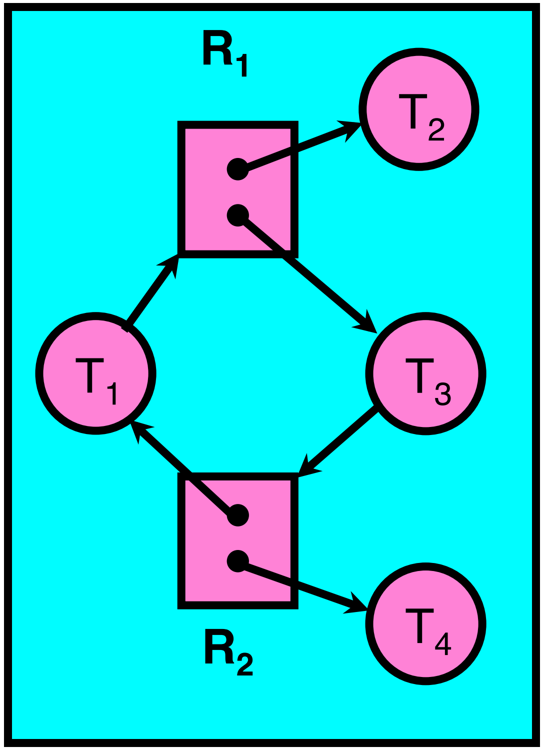
```
[Avail] = [FreeResources]
Add all nodes to UNFINISHED
do {
   done = true
   Foreach node in UNFINISHED {
      if ([Request_node] <= [Avail]) {
         remove node from UNFINISHED
         [Avail] = [Avail] + [Alloc_node]
         done = false
      }
   }
} until(done)
```



  - Nodes left in UNFINISHED ⇒ deadlocked

Deadlock Detection Algorithm Example

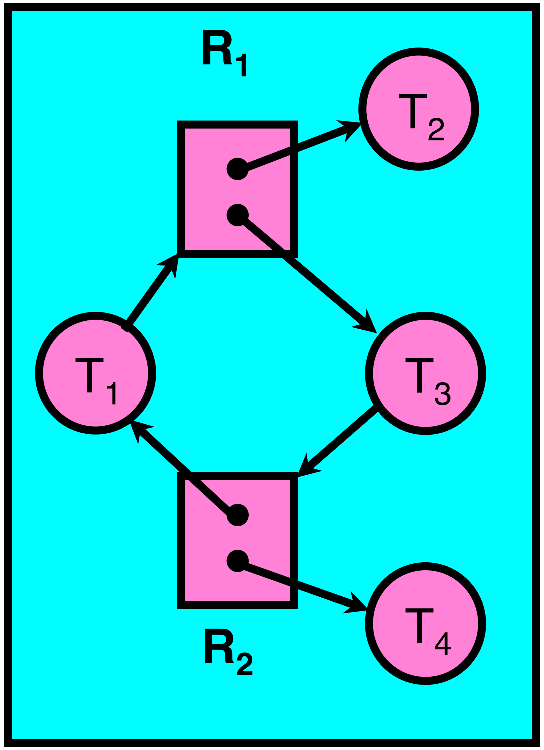
```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [0,0]
UNFINISHED = {T1,T2,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([Requestnode] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [Allocnode]
      done = false
    }
  }
} until(done)
```



Deadlock Detection Algorithm Example

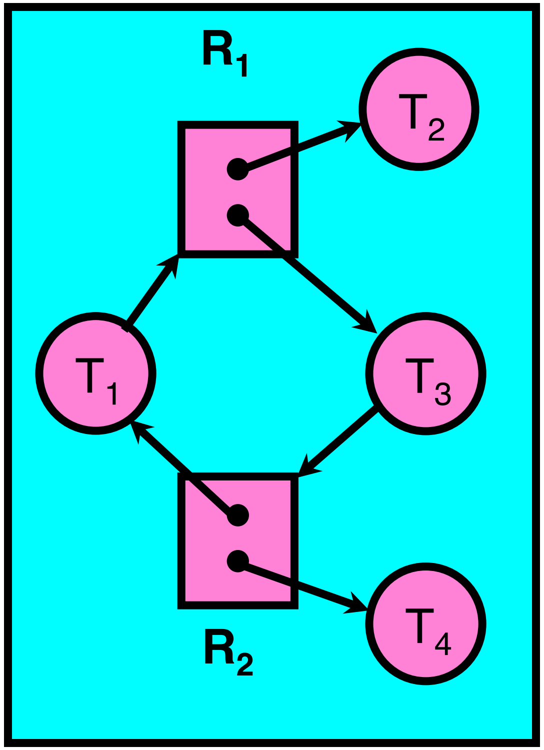
```
[Request_T1] = [1,0]; Alloc_T1 = [0,1]
[Request_T2] = [0,0]; Alloc_T2 = [1,0]
[Request_T3] = [0,1]; Alloc_T3 = [1,0]
[Request_T4] = [0,0]; Alloc_T4 = [0,1]
[Avail] = [0,0]
UNFINISHED = {T1,T2,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([Request_T1] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [Alloc_T1]
      done = false
    }
  }
} until(done)
```

False



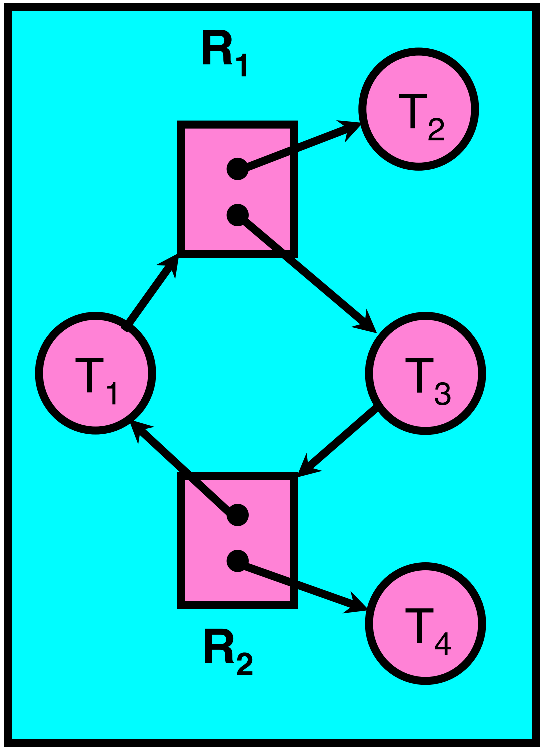
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [0,0]
UNFINISHED = {T1,T2,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([Requestnode] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [Allocnode]
      done = false
    }
  }
} until(done)
```



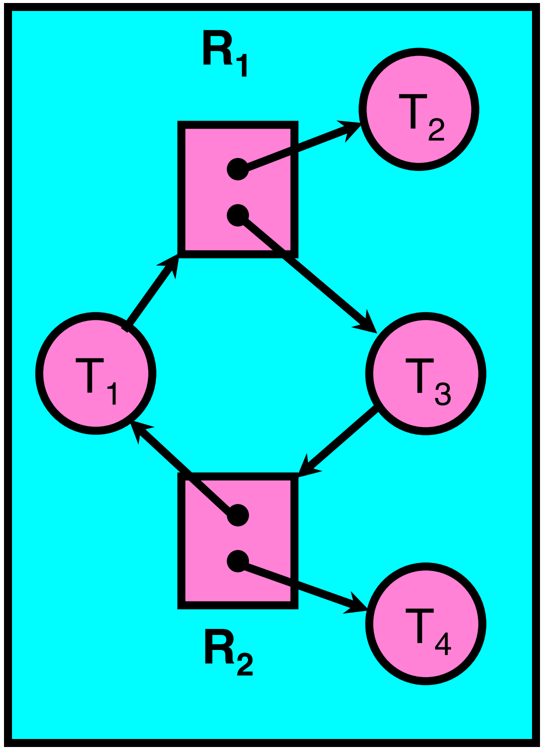
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [0,0]
UNFINISHED = {T1,T2,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT2] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT2]
      done = false
    }
  }
} until(done)
```



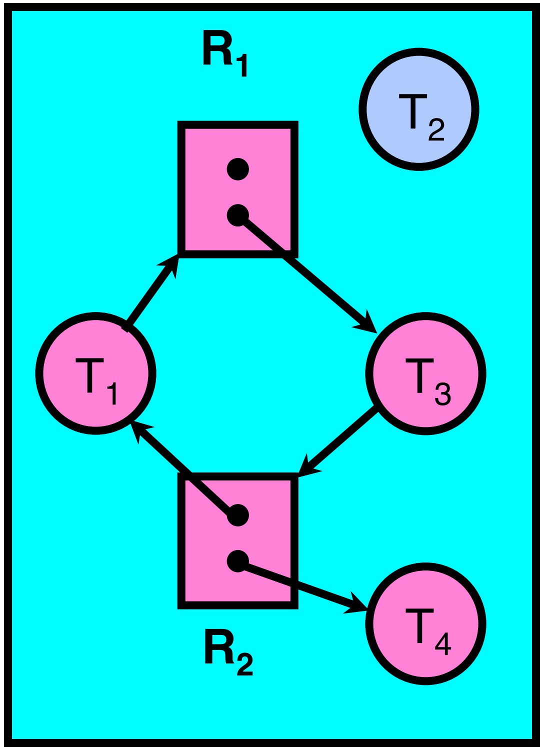
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [0,0]
UNFINISHED = {T1,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT2] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT2]
      done = false
    }
  }
} until(done)
```



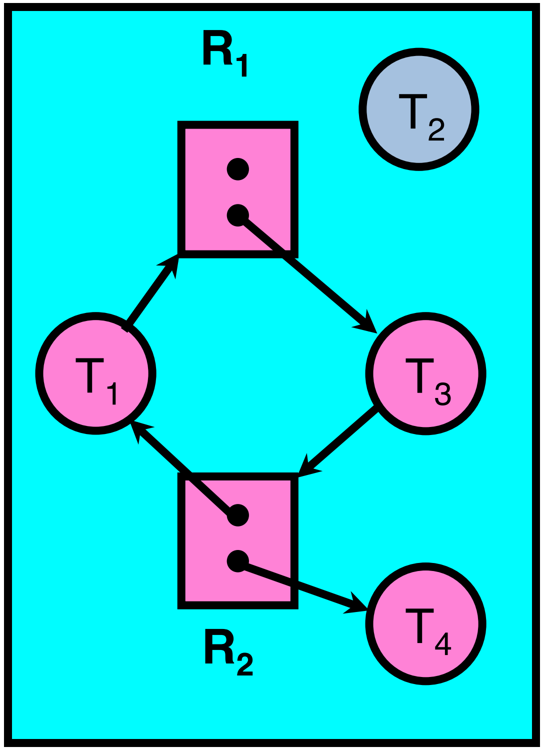
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,0]
UNFINISHED = {T1,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT2] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT2]
      done = false
    }
  }
} until(done)
```



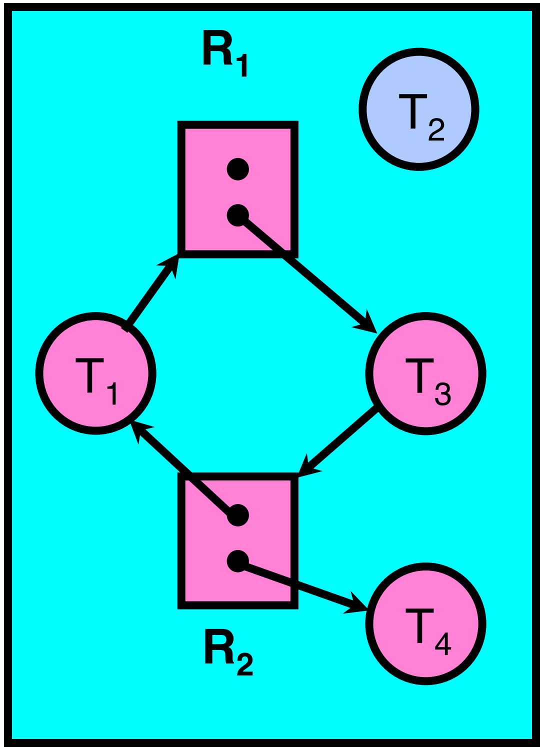
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,0]
UNFINISHED = {T1,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT2] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT2]
      done = false
    }
  }
} until(done)
```



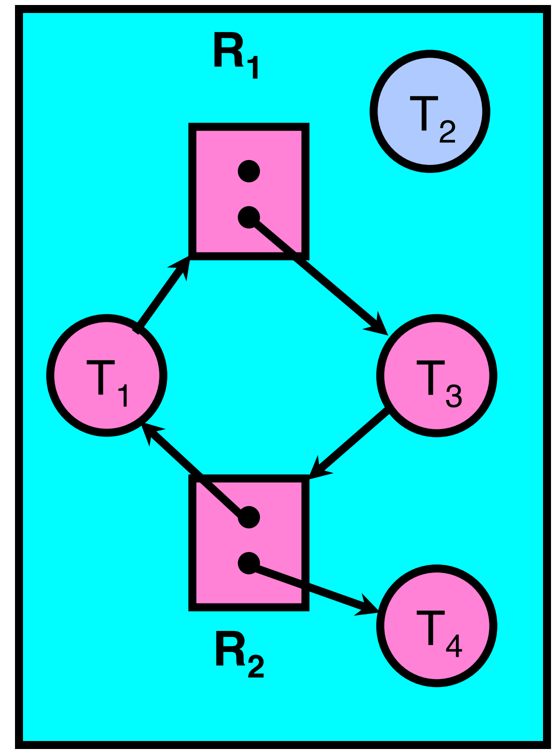
Deadlock Detection Algorithm Example

```
[Request_T1] = [1,0]; Alloc_T1 = [0,1]
[Request_T2] = [0,0]; Alloc_T2 = [1,0]
[Request_T3] = [0,1]; Alloc_T3 = [1,0]
[Request_T4] = [0,0]; Alloc_T4 = [0,1]
[Avail] = [1,0]
UNFINISHED = {T1,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([Request_node] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [Alloc_node]
      done = false
    }
  }
} until(done)
```



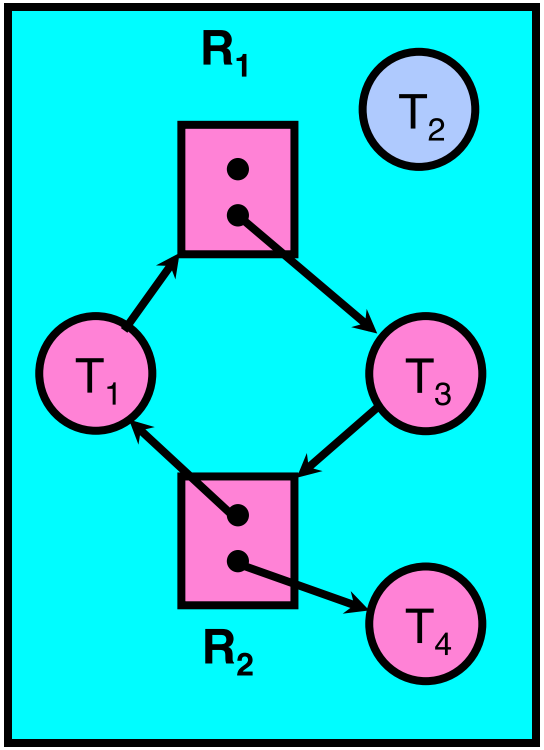
Deadlock Detection Algorithm Example

```
[Request_T1] = [1,0]; Alloc_T1 = [0,1]
[Request_T2] = [0,0]; Alloc_T2 = [1,0]
[Request_T3] = [0,1]; Alloc_T3 = [1,0]
[Request_T4] = [0,0]; Alloc_T4 = [0,1]
[Avail] = [1,0]
UNFINISHED = {T1,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([Request_T3] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [Alloc_T3]
      done = false
    }
  }
} until(done)
```



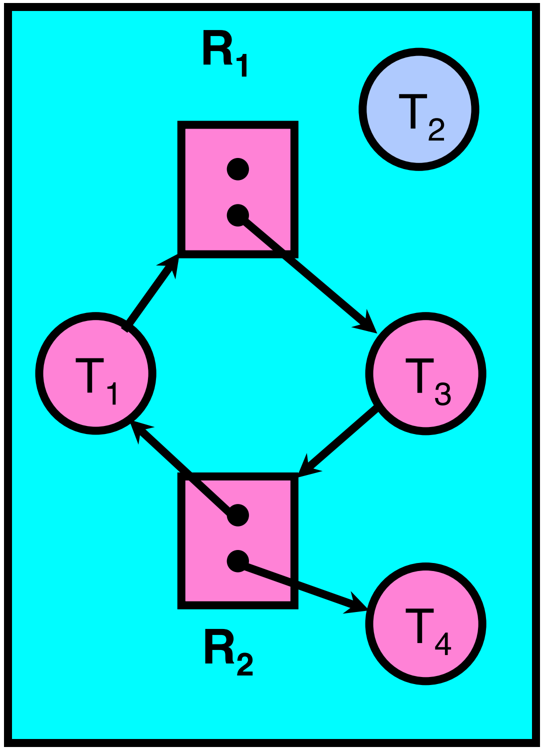
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,0]
UNFINISHED = {T1,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([Requestnode] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [Allocnode]
      done = false
    }
  }
} until(done)
```



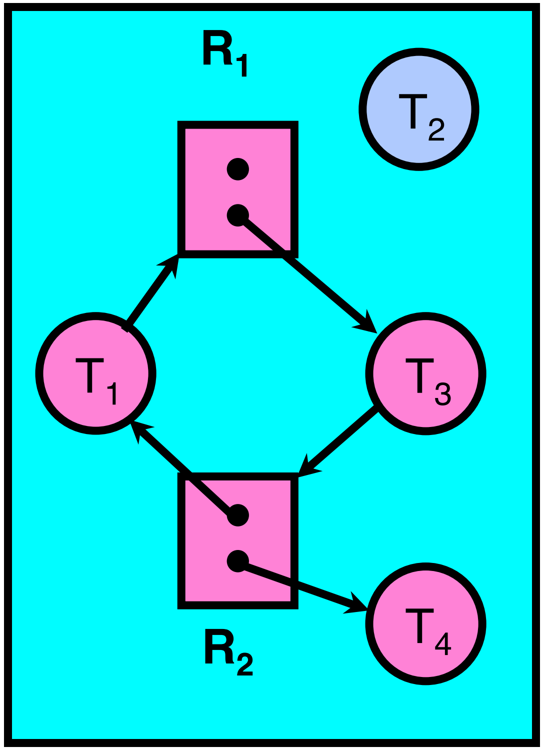
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,0]
UNFINISHED = {T1,T3,T4}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT4] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT4]
      done = false
    }
  }
} until(done)
```



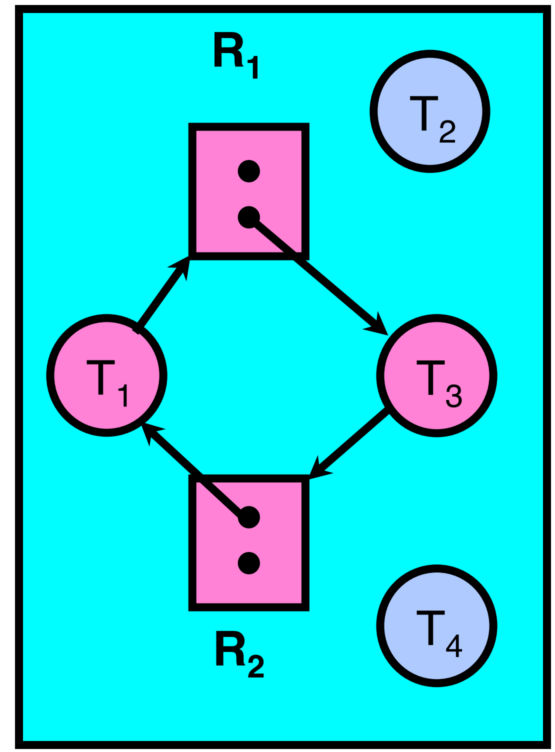
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,0]
UNFINISHED = {T1,T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT4] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT4]
      done = false
    }
  }
} until(done)
```



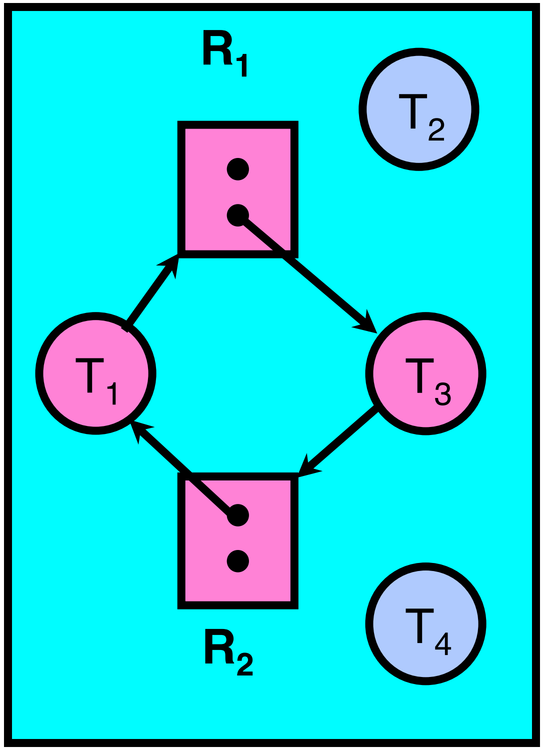
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,1]
UNFINISHED = {T1,T3}


do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT4] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT4]
      done = false
    }
  }
} until(done)
```



Deadlock Detection Algorithm Example

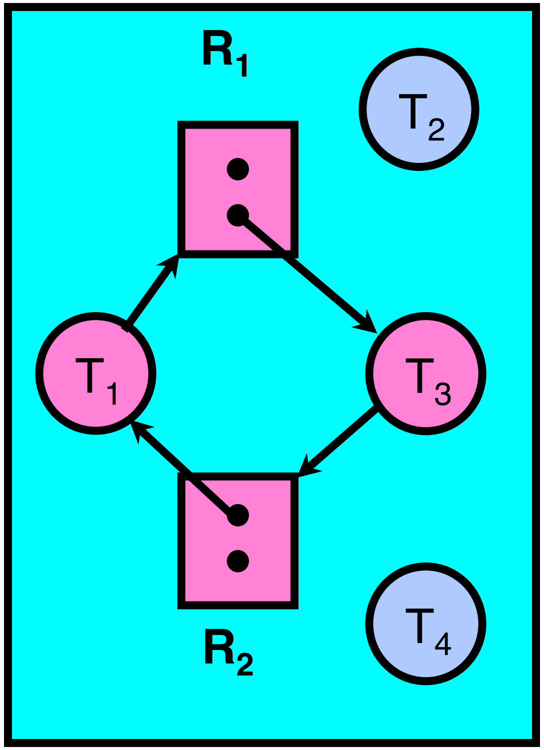
```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,1]
UNFINISHED = {T1,T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT4] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT4]
      done = false
    }
  }
} until(done)
```



Deadlock Detection Algorithm Example

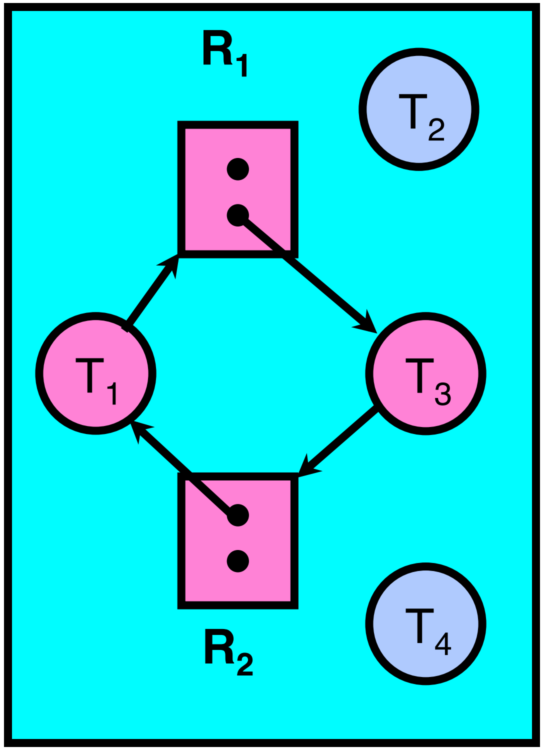
```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,1]
UNFINISHED = {T1,T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT4] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT4]
      done = false
    }
  }
} until(done)
```

False



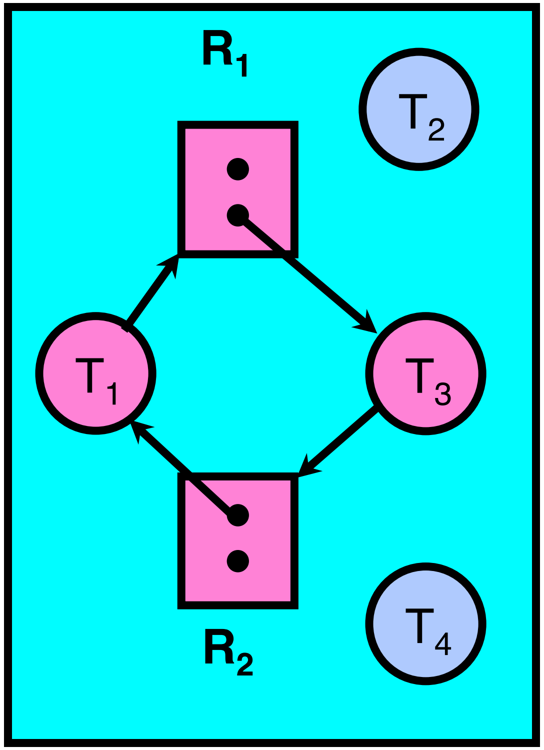
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,1]
UNFINISHED = {T1,T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([Requestnode] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [Allocnode]
      done = false
    }
  }
} until(done)
```



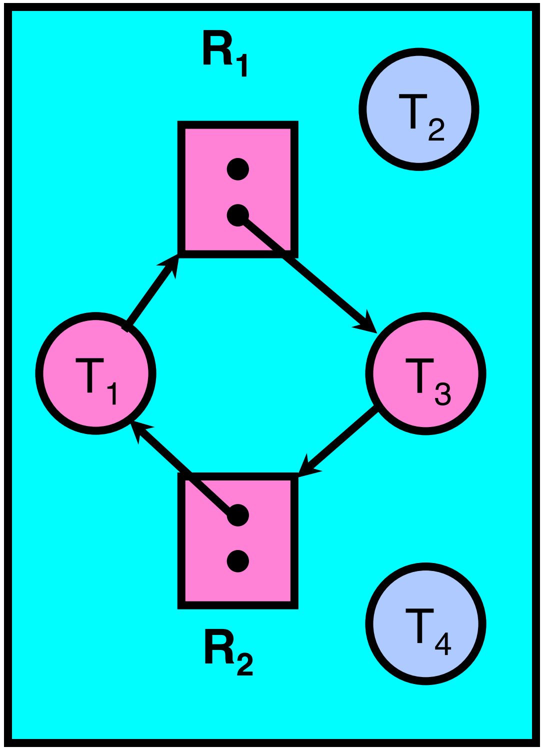
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,1]
UNFINISHED = {T1,T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT1] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT1]
      done = false
    }
  }
} until(done)
```



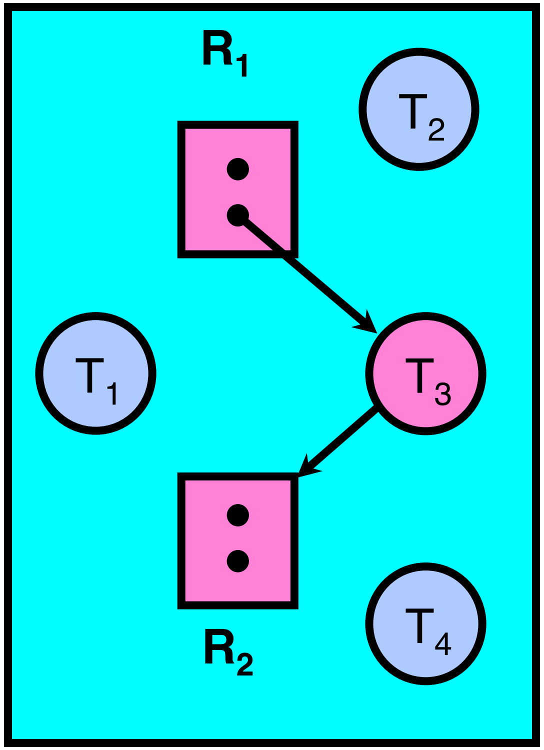
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,1]
UNFINISHED = {T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT1] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT1]
      done = false
    }
  }
} until(done)
```



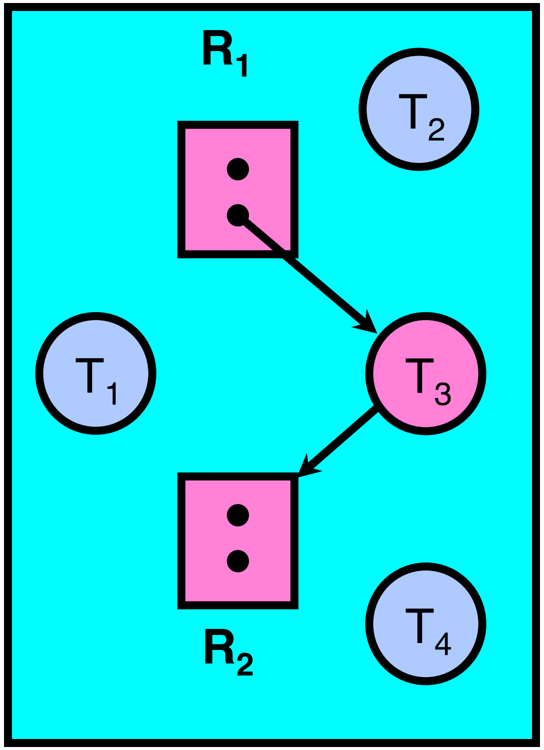
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,2]
UNFINISHED = {T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT1] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT1]
      done = false
    }
  }
} until(done)
```



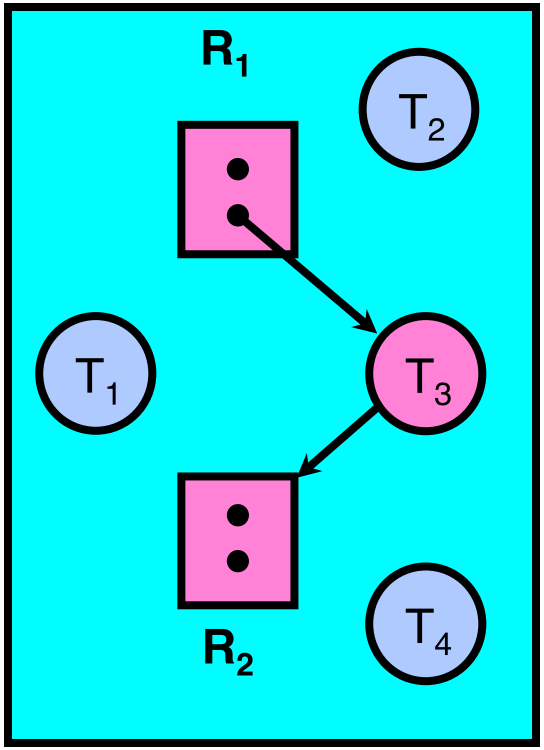
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,2]
UNFINISHED = {T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT1] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT1]
      done = false
    }
  }
} until(done)
```



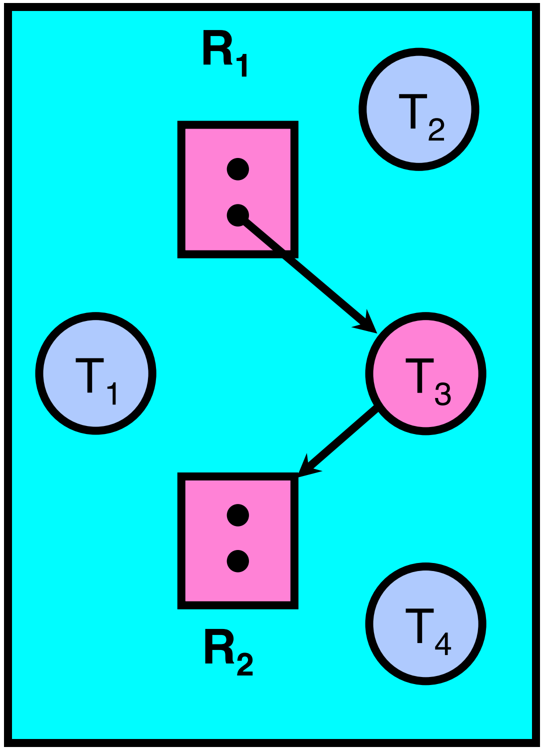
Deadlock Detection Algorithm Example

```
[Request_T1] = [1,0]; Alloc_T1 = [0,1]
[Request_T2] = [0,0]; Alloc_T2 = [1,0]
[Request_T3] = [0,1]; Alloc_T3 = [1,0]
[Request_T4] = [0,0]; Alloc_T4 = [0,1]
[Avail] = [1,2]
UNFINISHED = {T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([Request_node] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [Alloc_node]
      done = false
    }
  }
} until(done)
```



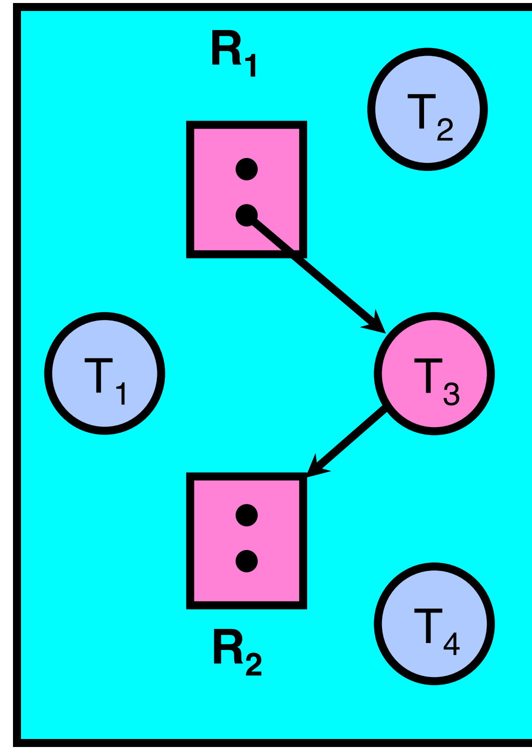
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,2]
UNFINISHED = {T3}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT3] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT3]
      done = false
    }
  }
} until(done)
```



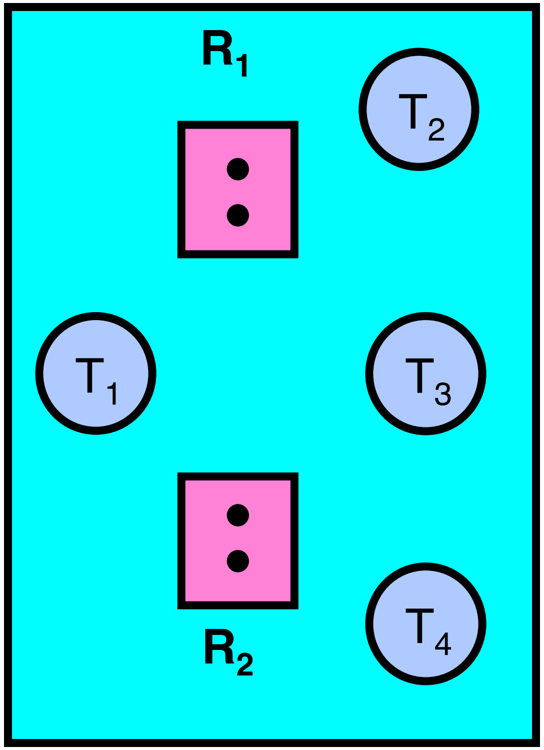
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [1,2]
UNFINISHED = {}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT3] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT3]
      done = false
    }
  }
} until(done)
```



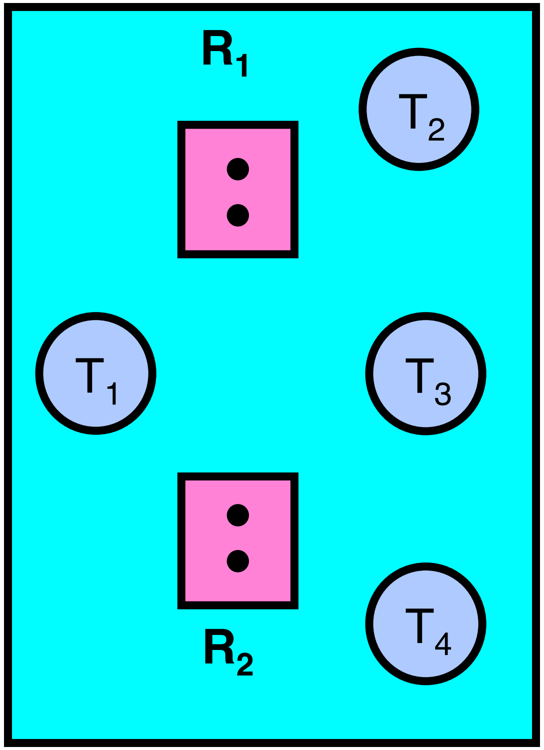
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [2,2]
UNFINISHED = {}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT3] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT3]
      done = false
    }
  }
} until(done)
```



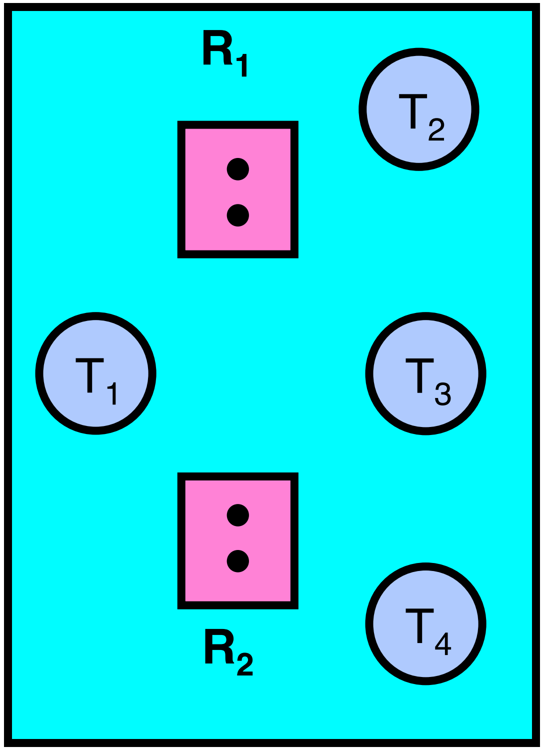
Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [2,2]
UNFINISHED = {}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT3] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT3]
      done = false
    }
  }
} until(done)
```



Deadlock Detection Algorithm Example

```
[RequestT1] = [1,0]; AllocT1 = [0,1]
[RequestT2] = [0,0]; AllocT2 = [1,0]
[RequestT3] = [0,1]; AllocT3 = [1,0]
[RequestT4] = [0,0]; AllocT4 = [0,1]
[Avail] = [2,2]
UNFINISHED = {}

do {
  done = true
  Foreach node in UNFINISHED {
    if ([RequestT3] <= [Avail]) {
      remove node from UNFINSHED
      [Avail] = [Avail] + [AllocT3]
      done = false
    }
  }
} until(done)
```



DONE!

Banker's Algorithm for Preventing Deadlock

- Toward right idea:
  - State maximum resource needs in advance
  - Allow particular thread to proceed if:

    (available resources - #requested) ≥ max remaining that might be needed by any thread

- Banker's algorithm (less conservative):
  - Allocate resources dynamically
    - Evaluate each request and grant if some ordering of threads is still deadlock free afterward
    - Keeps system in a "SAFE" state, i.e. there exists a sequence $\{T_1, T_2, \ldots T_n\}$ with T_1 requesting all remaining resources, finishing, then T_2 requesting all remaining resources, etc..
  - Algorithm allows the sum of maximum resource needs of all current threads to be greater than total resources

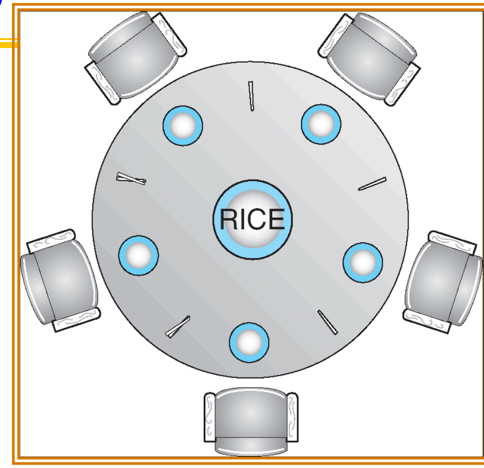
Banker's Algorithm

- Technique: pretend each request is granted, then run deadlock detection algorithm, substitute
  $([Request_{node}] \le [Avail]) \rightarrow ([Max_{node}]-[Alloc_{node}] \le [Avail])$

`[FreeResources]:`	Current free resources each type
`[Alloc`$_X$`]:`	Current resources held by thread X
`[Max`$_X$`]:`	Max resources requested by thread X

```
   [Avail] = [FreeResources]
Add all nodes to UNFINISHED
do {
   done = true
   Foreach node in UNFINISHED {
  if ([Max_node]-[Alloc_node]<= [Avail]) {
        remove node from UNFINISHED
        [Avail] = [Avail] + [Alloc_node]
        done = false
     }
   }
} until(done)
```

Banker's Algorithm Example



- Banker's algorithm with dining philosophers
  - "Safe" (won't cause deadlock) if when try to grab chopstick either:
    - Not last chopstick
    - Is last chopstick but someone will have two afterwards
  - What if k-handed philosophers? Don't allow if:
    - It's the last one, no one would have k
    - It's 2nd to last, and no one would have k-1
    - It's 3rd to last, and no one would have k-2
    - …

Summary: Deadlock

- Four conditions for deadlocks
  - Mutual exclusion
    - Only one thread at a time can use a resource
  - Hold and wait
    - Thread holding at least one resource is waiting to acquire additional resources held by other threads
  - No preemption
    - Resources are released only voluntarily by the threads
  - Circular wait
    - ∃ set $\{T_1, \ldots, T_n\}$ of threads with a cyclic waiting pattern
- Starvation vs. Deadlock
  - Starvation: thread waits indefinitely
  - Deadlock: circular waiting for resources
- Deadlock detection and preemption
- Deadlock prevention
  - Loop Detection, Banker's algorithm