Distributed Mutual Exclusion

Last time…

- Synchronizing real, distributed clocks
- Logical time and concurrency
- Lamport clocks and total-order Lamport clocks
- Vector clocks
- Happens-before relation

Goals of distributed mutual exclusion

- Much like regular mutual exclusion
  - Safety: mutual exclusion
  - Liveness: progress
  - Fairness: bounded wait and in-order
- Secondary goals:
  - reduce message traffic
  - minimize synchronization delay
    - i.e., switch quickly between waiting processes

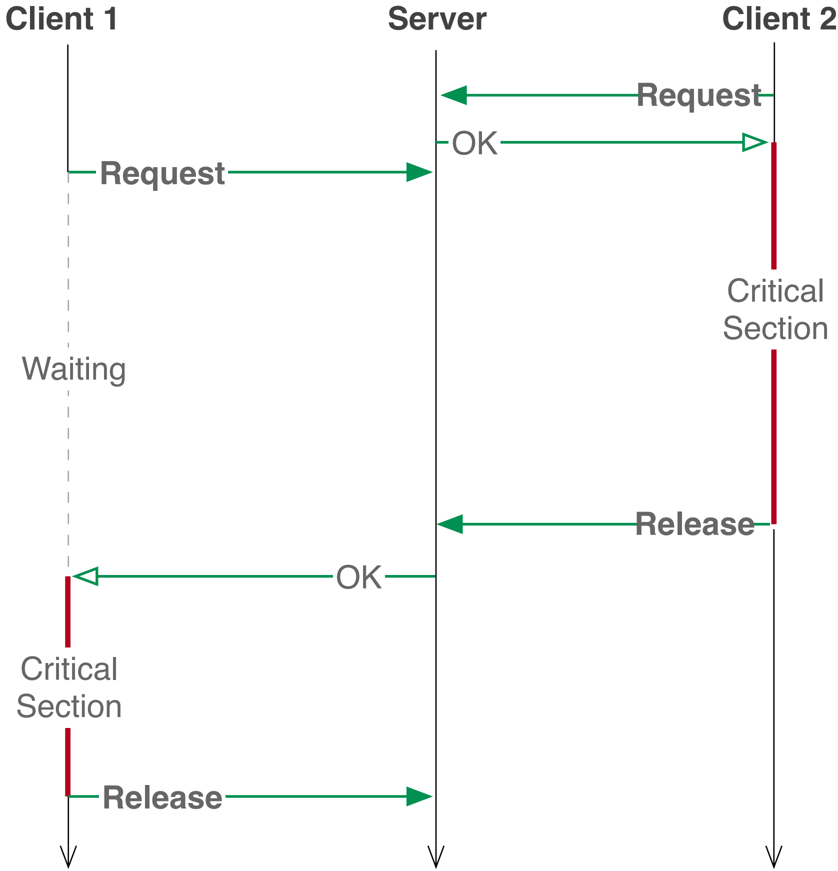
By logical time!

Distributed mutex is different

- Regular mutual exclusion solved using shared state, e.g.
  - atomic test-and-set of a shared variable…
  - shared queue…
- We solve distributed mutual exclusion with message passing
  - Note: we assume the network is reliable but asynchronous…but processes might fail!

Solution 1: A central mutex server

- To enter critical section:
  - send REQUEST to central server, wait for permission
- To leave:
  - send RELEASE to central server

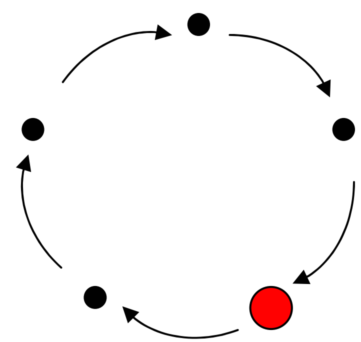

Client 1
Server
Client 2
Request
OK
Request
Critical
Section
Waiting
Release
OK
Critical
Section
Release

Solution 1: A central mutex server

- Advantages:
  - Simple (we like simple!)
  - Only 3 messages required per entry/exit
- Disadvantages:
  - Central point of failure
  - Central performance bottleneck
  - With an asynchronous network, impossible to achieve in-order fairness
  - Must elect/select central server

Solution 2: A ring-based algorithm

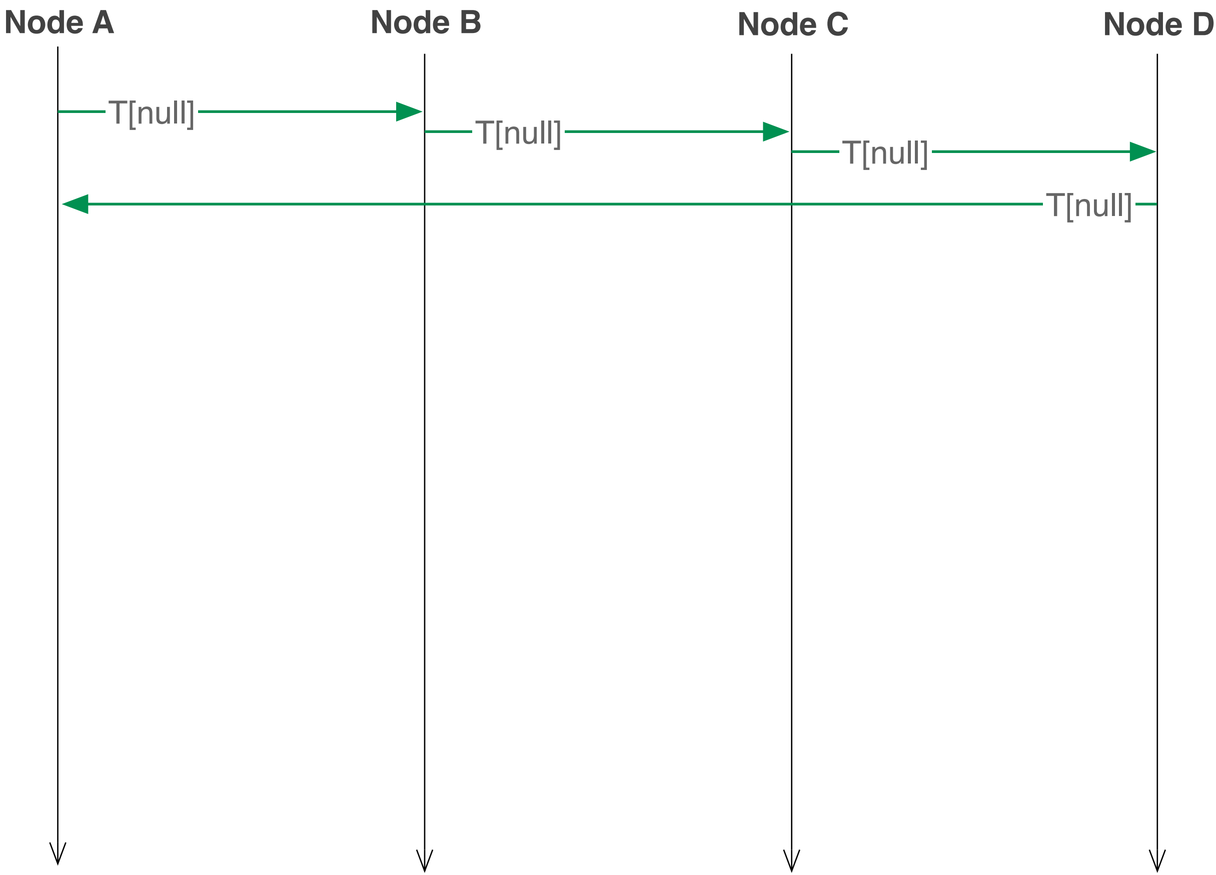
- Pass a token around a ring
  - Can enter critical section only if you hold the token
- Problems:
  - Not in-order
  - Long synchronization delay
    - Need to wait for up to *N-1* messages, for *N* processors
  - Very unreliable
    - Any process failure breaks the ring



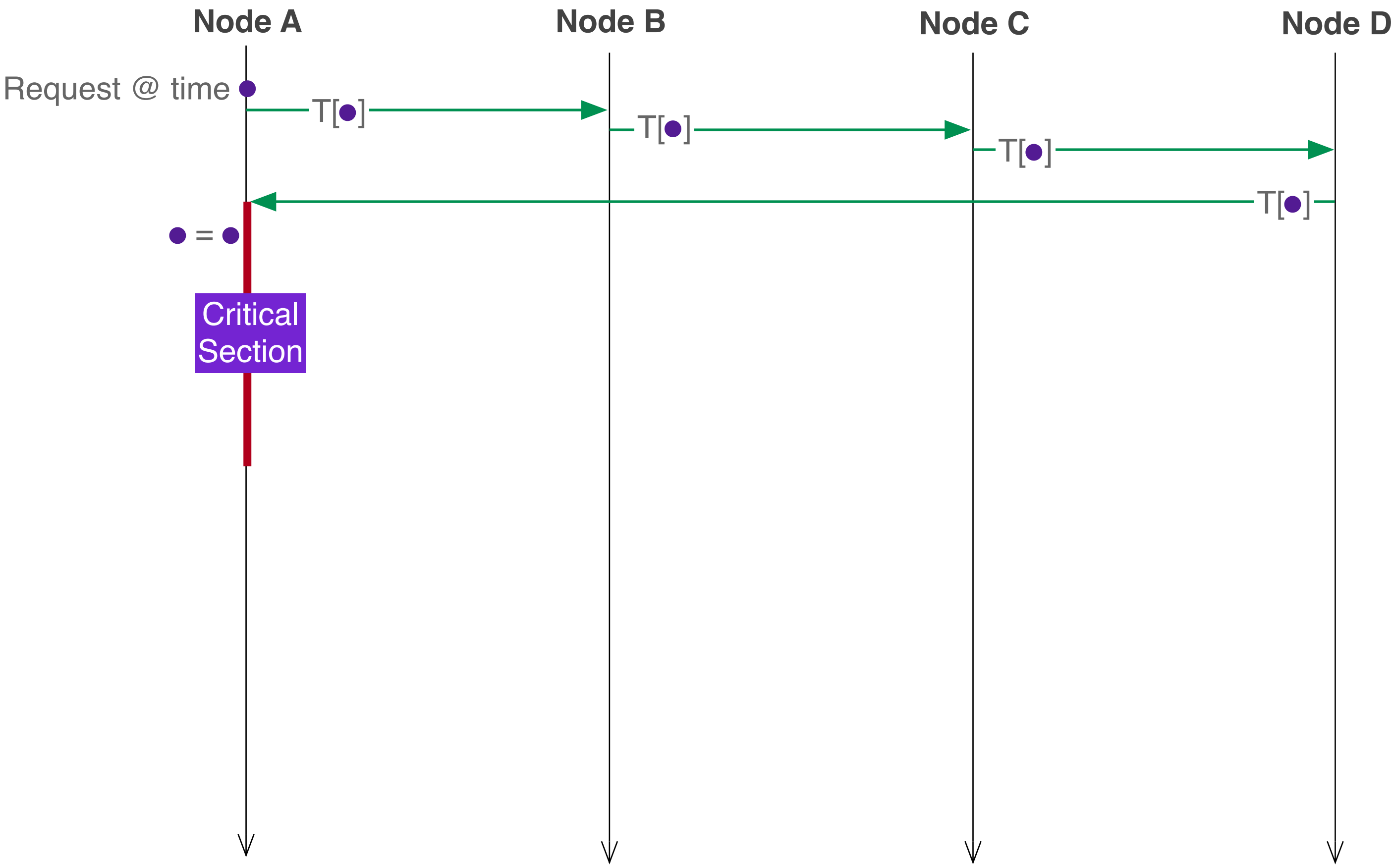
2': A fair ring-based algorithm

- Token contains the time t of the earliest known outstanding request
- To enter critical section:
  - Stamp your request with the current time T_r, wait for token
- When you get token with time t while waiting with request from time T_r, compare T_r to t:
  - If $T_r = t$: hold token, run critical section
  - If $T_r > t$: pass token
  - If t not set or $T_r < t$: set token-time to T_r, pass token, wait for token
- To leave critical section:
  - Set token-time to null (i.e., unset it), pass token

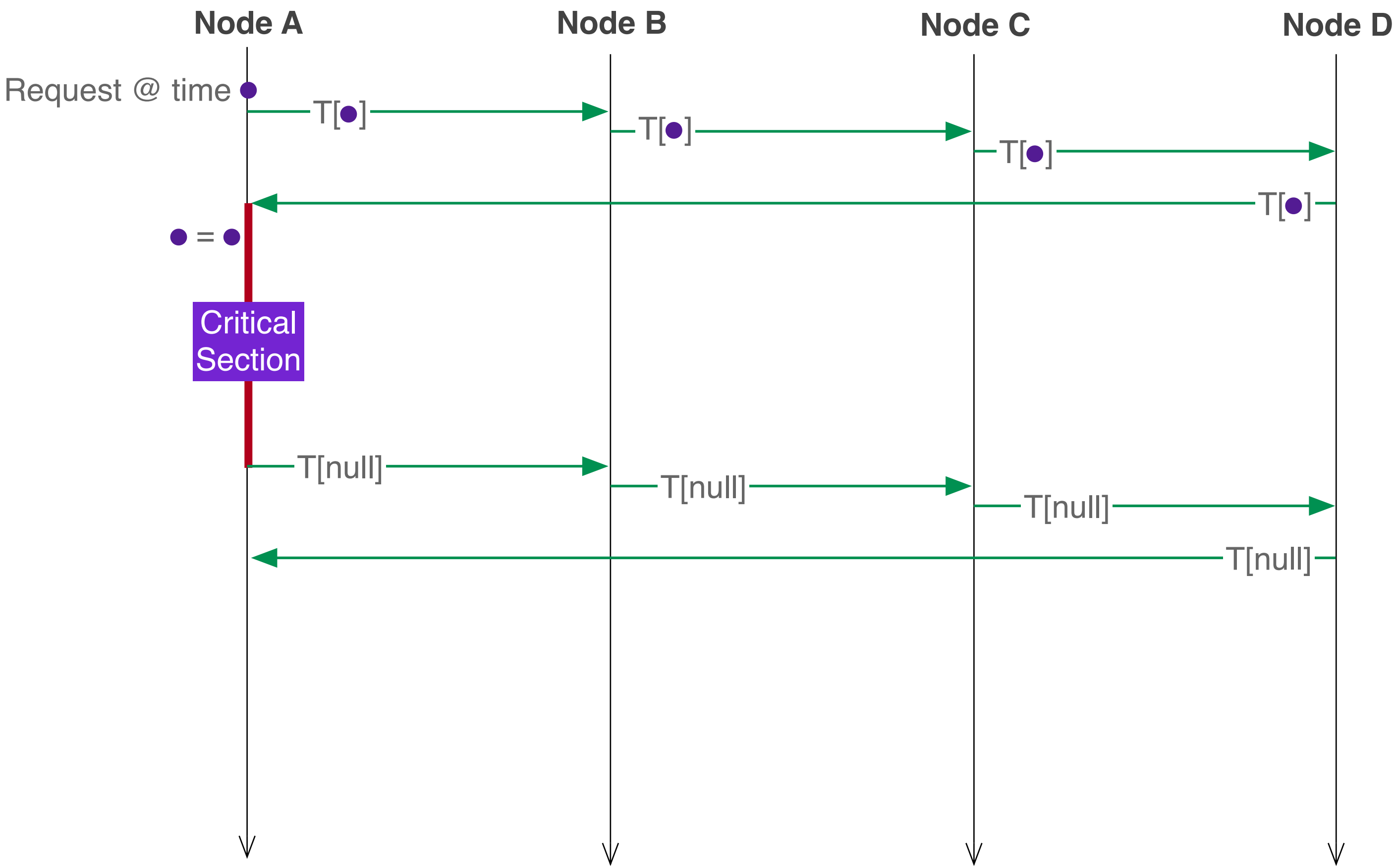
Base case: null token circulates around the system



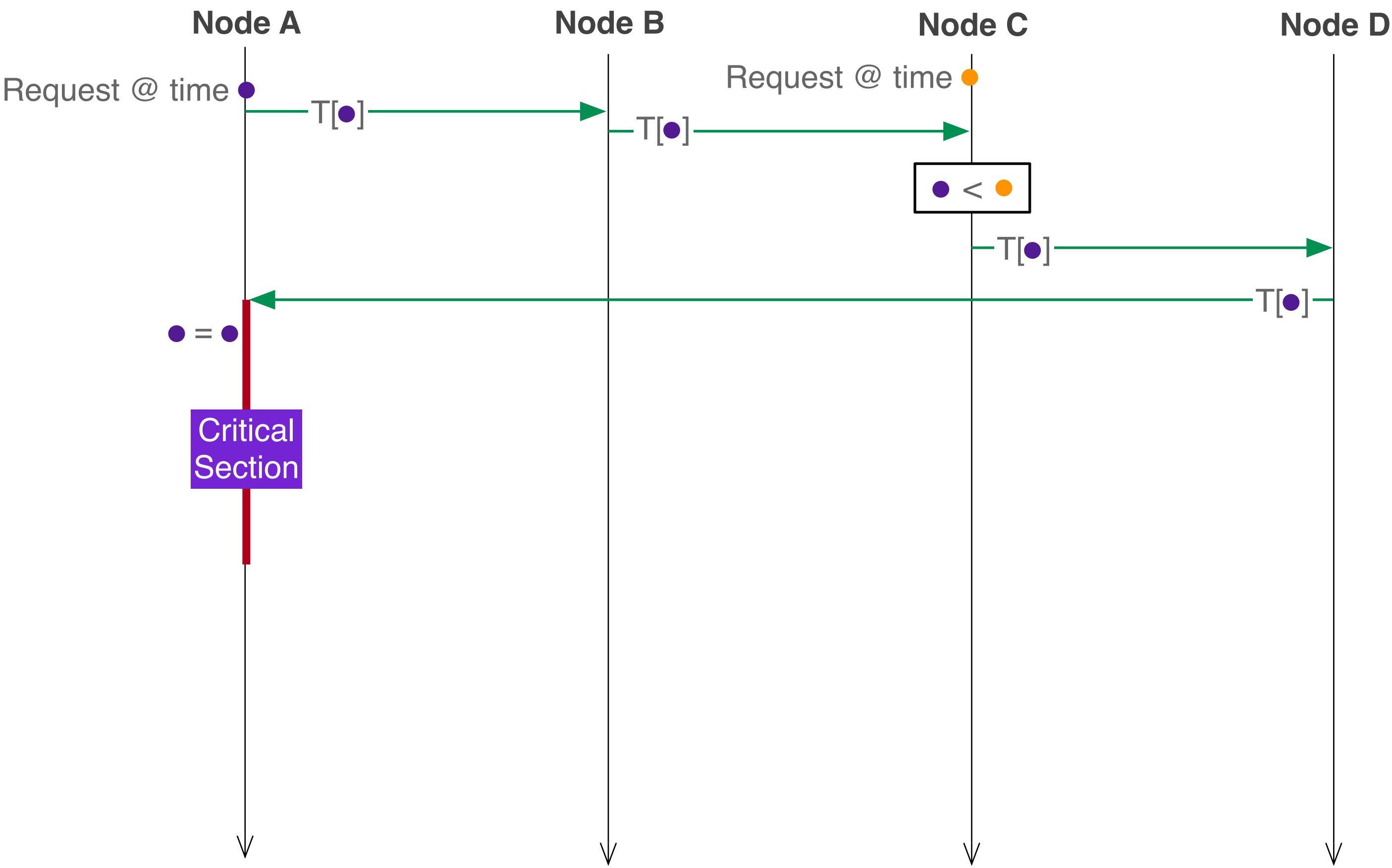
1/2 Simple case: one request



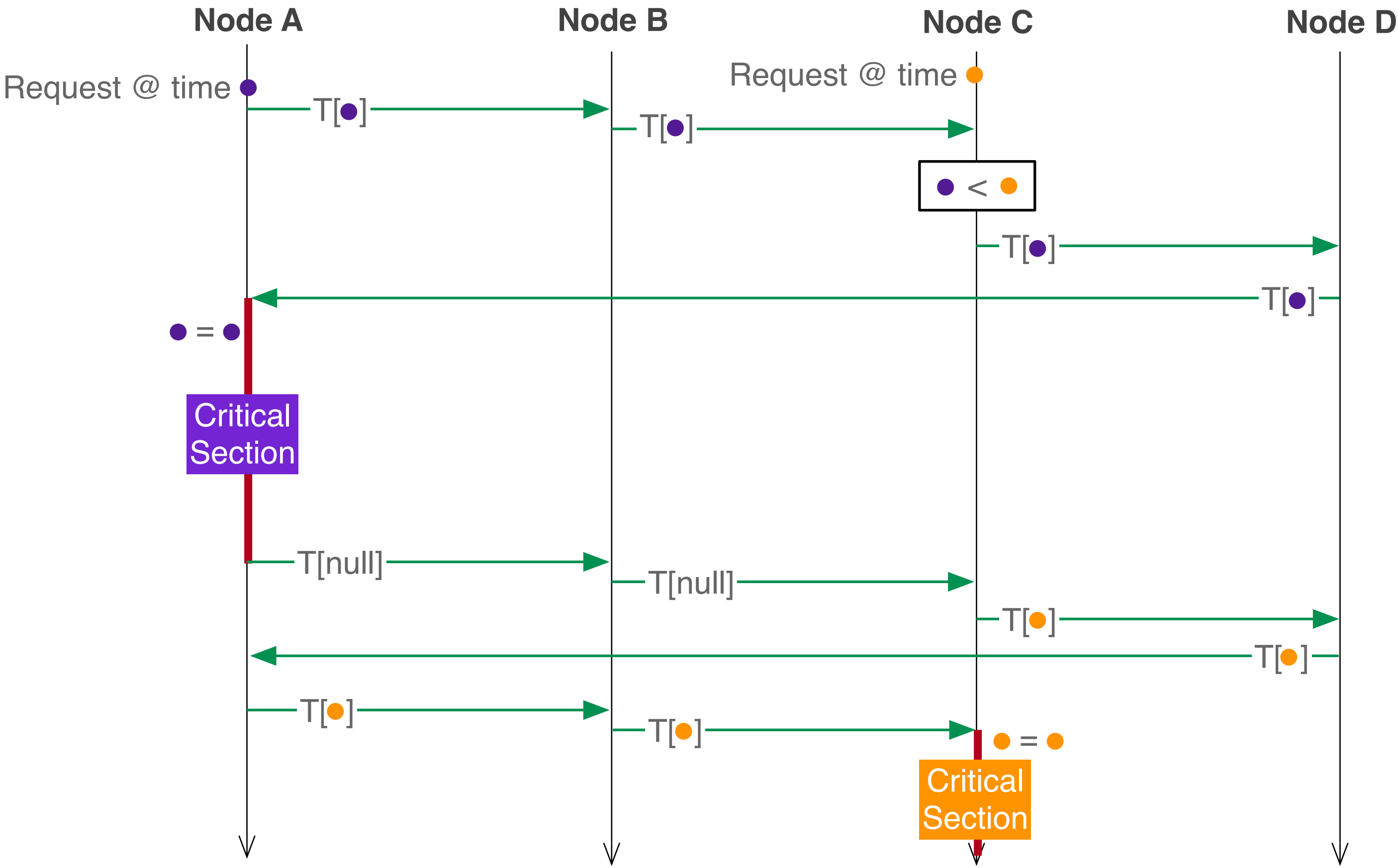
2/2 Simple case: one request



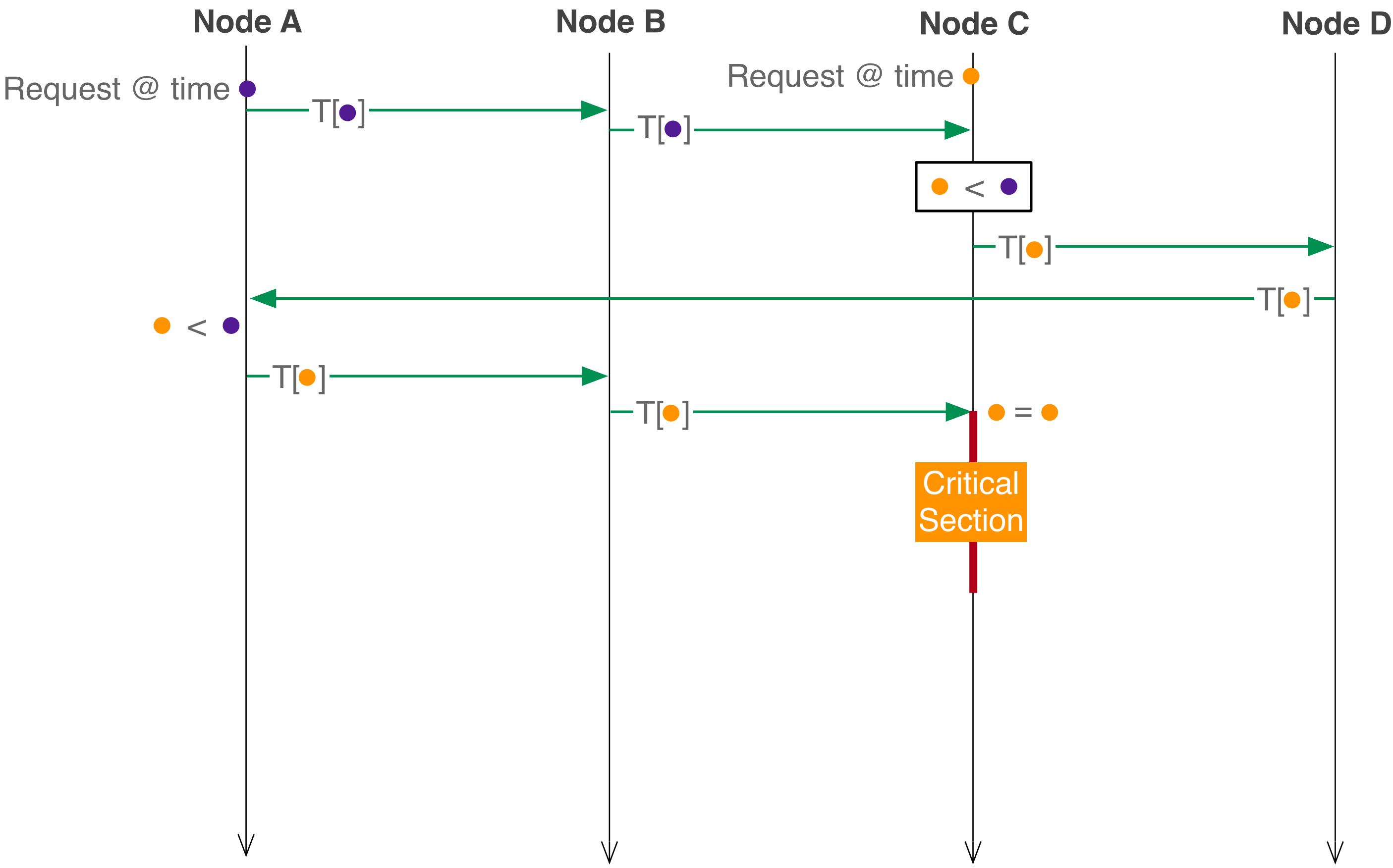
1/2 Competing requests: ● < ●



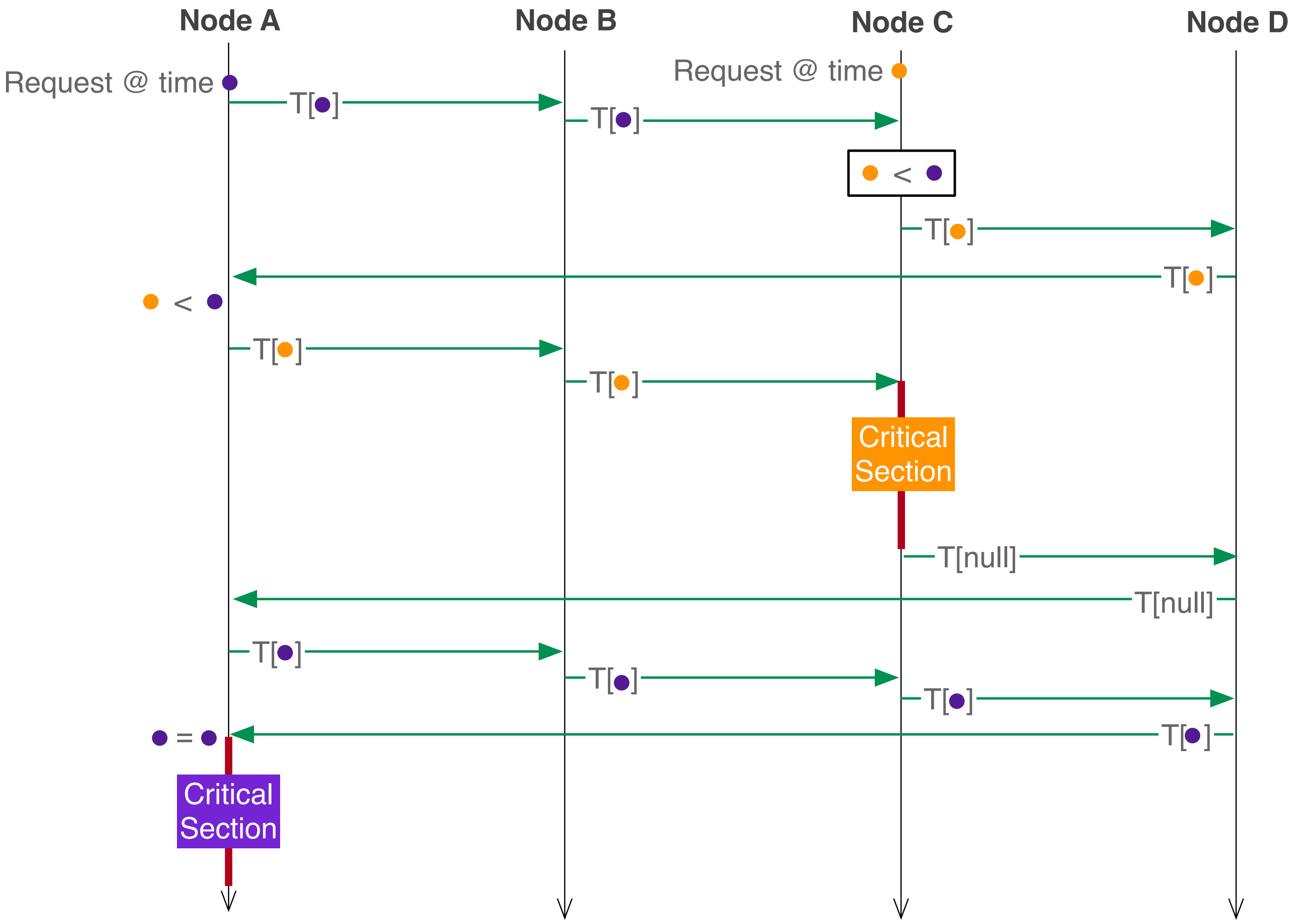
2/2 Competing requests: ● < ●



1/2 Competing requests: ● < ●



2/2 Competing requests: ● < ●



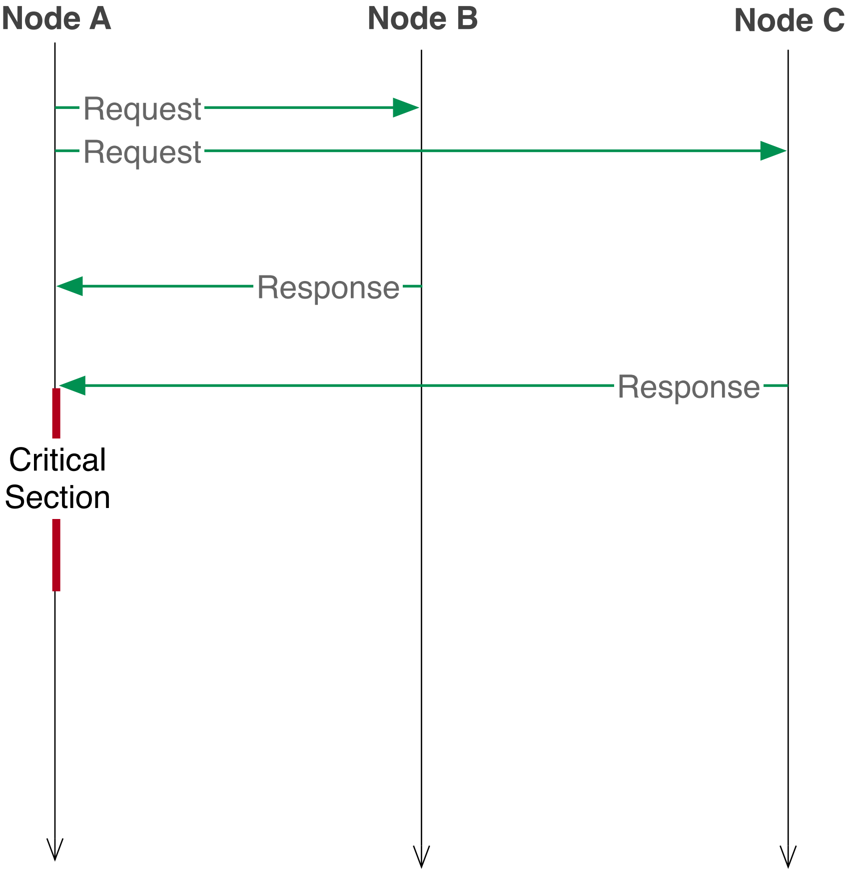
Solution 3: Ricart and Agrawala dist. mutual exclusion alg

- Relies on Lamport totally ordered clocks, having the following properties:
  - For any events e, e’ such that e --> e’ (causality ordering), T(e) < T(e’)
  - For any distinct events e, e’, T(e) != T(e’)

General idea

- When want to enter critical section (C.S.) node i sends time-stamped request to all other nodes. These other nodes reply (eventually).
- When i receives n-1 replies, then can enter C.S.
- Trick: Node j having earlier request doesn't reply to i until after it has completed its C.S.

Ricart-Agrawala overview



Notation

- Ni = {1, 2, ..., i-1, i+1, ..., n} (n is the number of processes)
- Message types
  - (Request, i, T): Process i requests lock with timestamp T
  - (Reply, j): Process j responds to some request for lock
- For each node i, maintain following values:
  - Ti(): Function that returns value of local Lamport clock
  - should_defer: Boolean Set when process i should defer replies to requests
  - Tr: Time stamp of pending local request
  - R: Subset of Ni. Set of processes from which have received reply
  - D: Subset of Ni. Set of processes for which i has deferred the reply to their requests
  - lock(), unlock(): A local mutex lock, to keep the two threads from interfering with each other

Design

- Process i consists of two threads. One servicing the application, and one monitoring the network.

```
Application thread:
 Request()                    // Request global mutex
 Wait for Notification // Wait until notified by network thread
 Critical Section            // Operate in exclusive mode
 Release()                    // Release mutex
```

Application functions

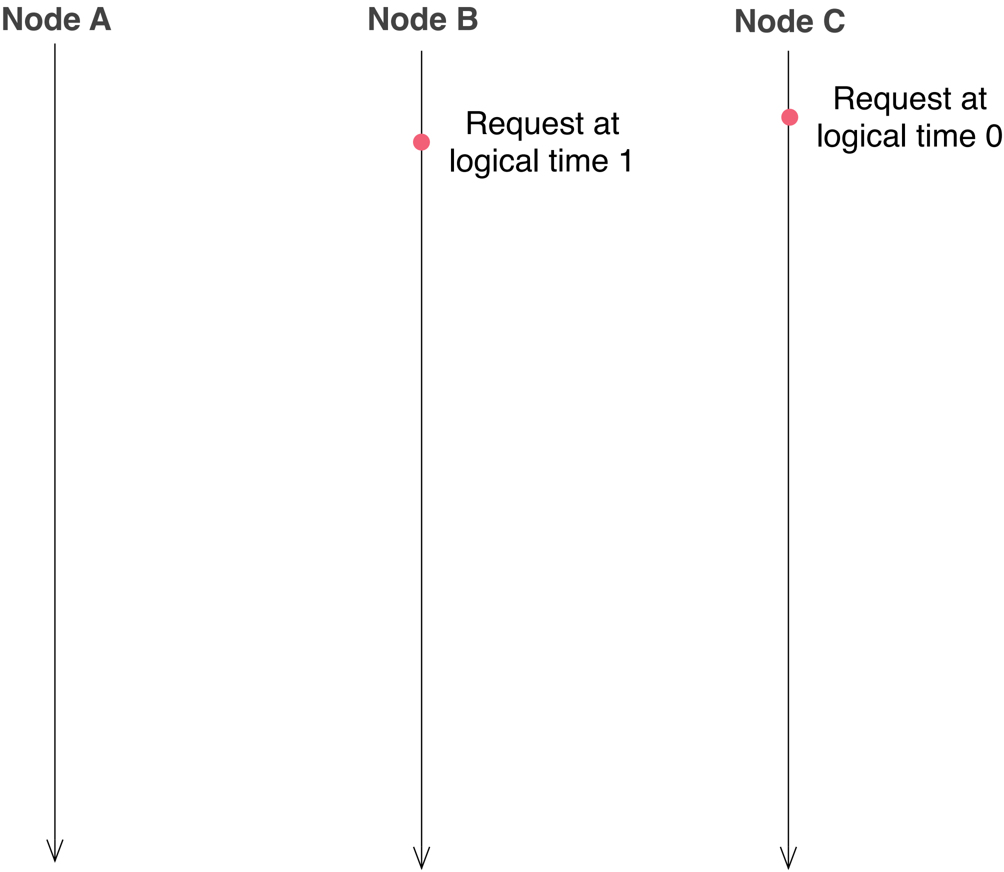
```
Request():
 lock()    // Don't want app/network fns to step on each other
 Tr = Ti() // Get time stamp
 R = {}
 D = {}
 should_defer = true
 Send (Request, i, Tr) to each j in Ni
 unlock()

Release():
 lock()
 should_defer = false
 Send (Reply, i) to each j in D
 unlock()
```

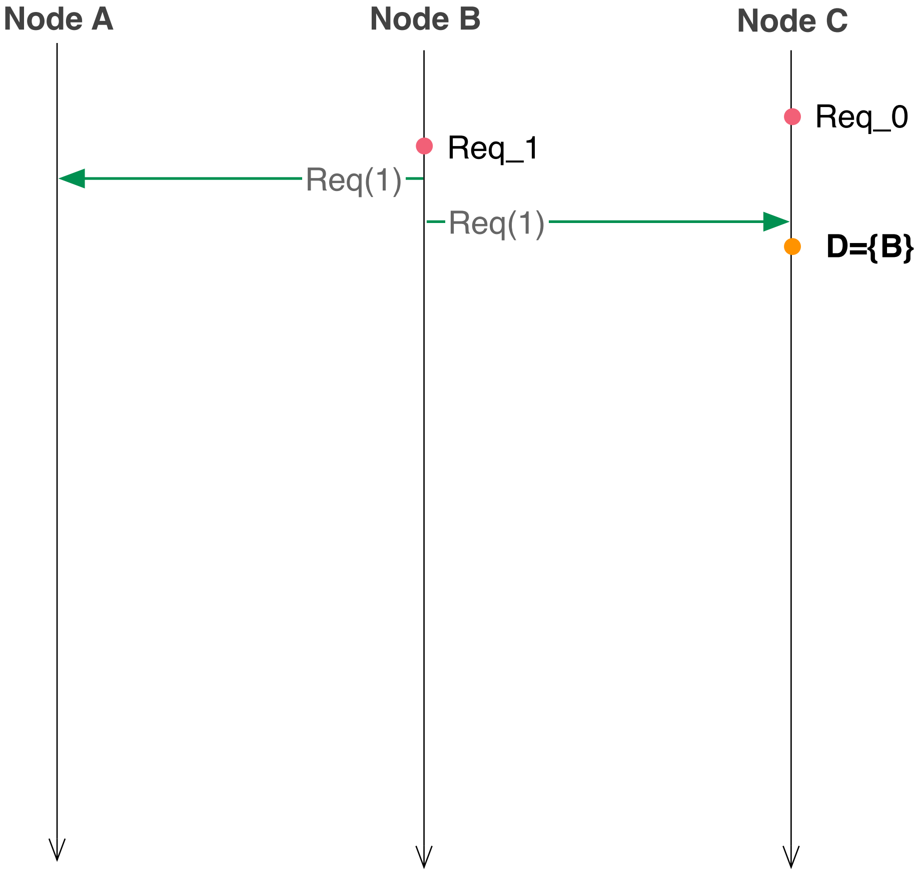
Network function

```
while true:
 m = Receive()
 lock()
 if m == (Request, j, T):
   if should_defer && Tr < T:
     D = D U {j} // Defer response to j
   else
     Send (Reply, i) to j
 else if m == (Reply, j):
   R = R U {j}
   if R == Ni
     Notify application
 unlock()
```

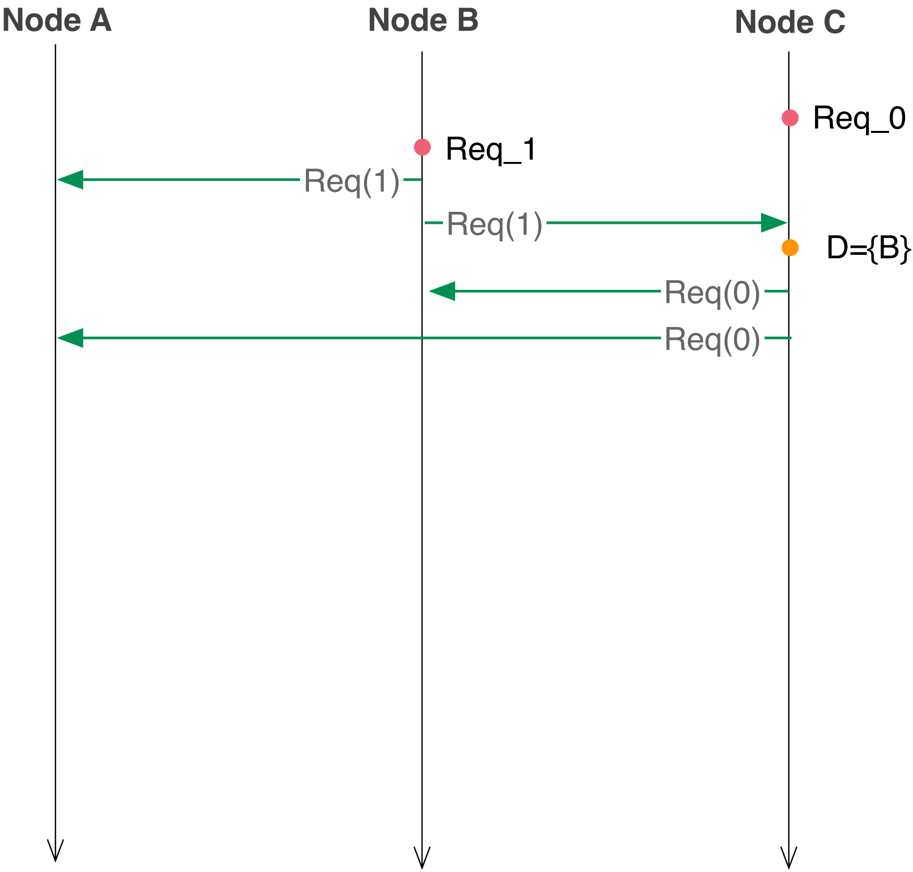
0/6 Ricart-Agrawala close-up



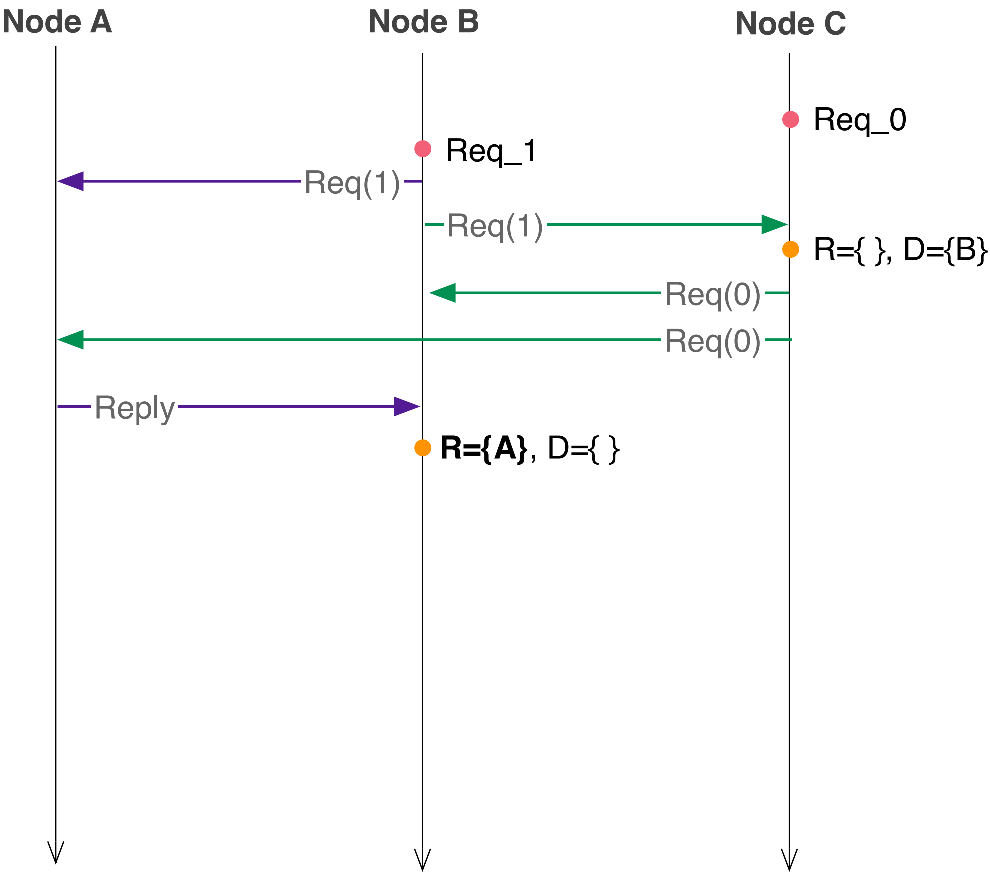
1/6 Ricart-Agrawala close-up



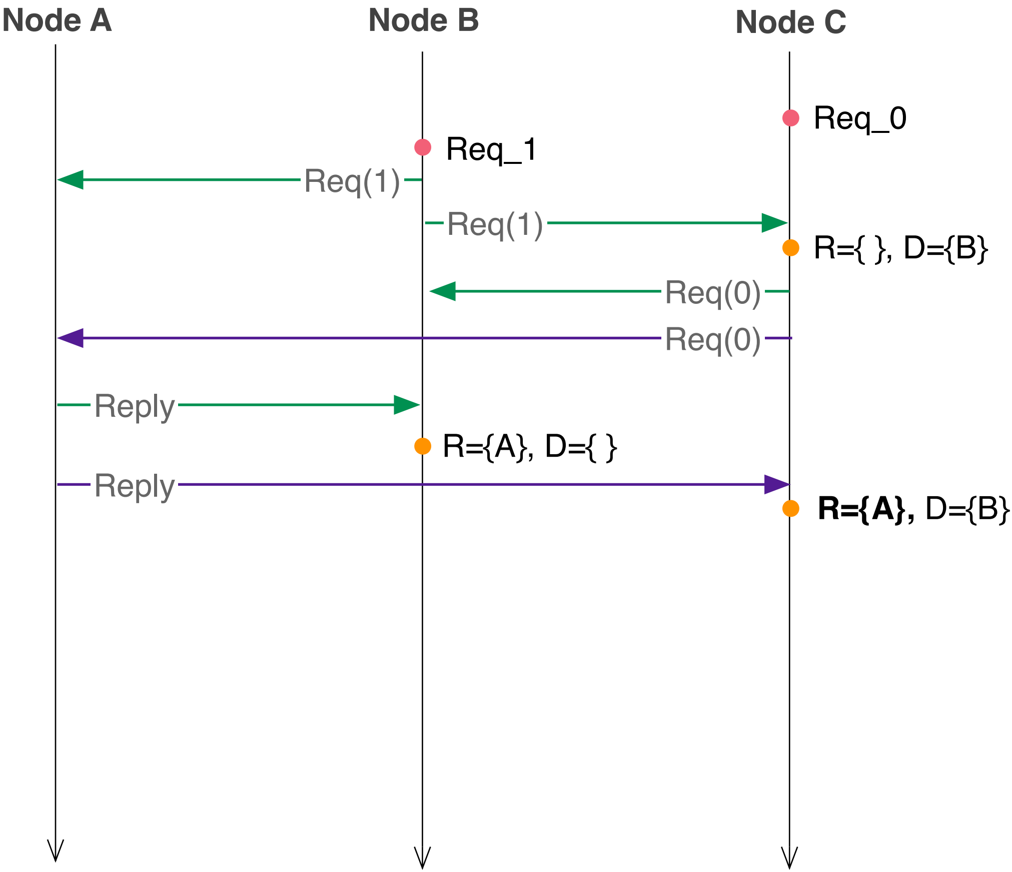
2/6 Ricart-Agrawala close-up



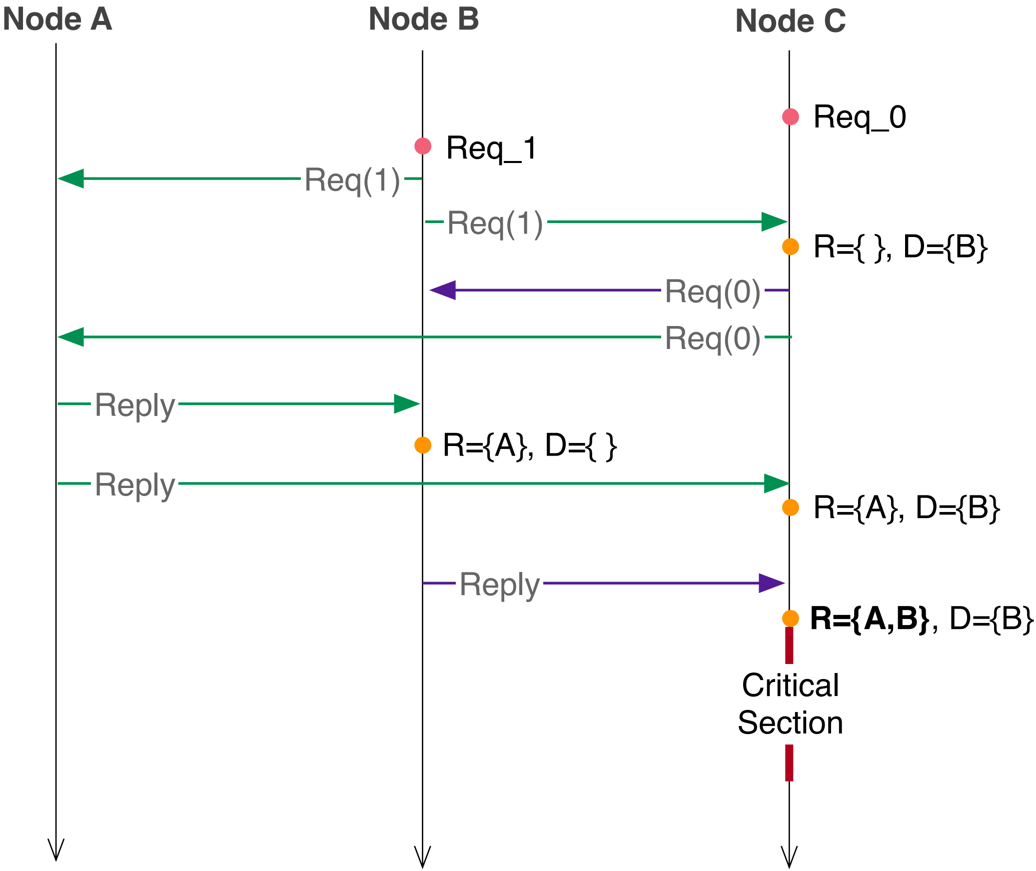
3/6 Ricart-Agrawala close-up



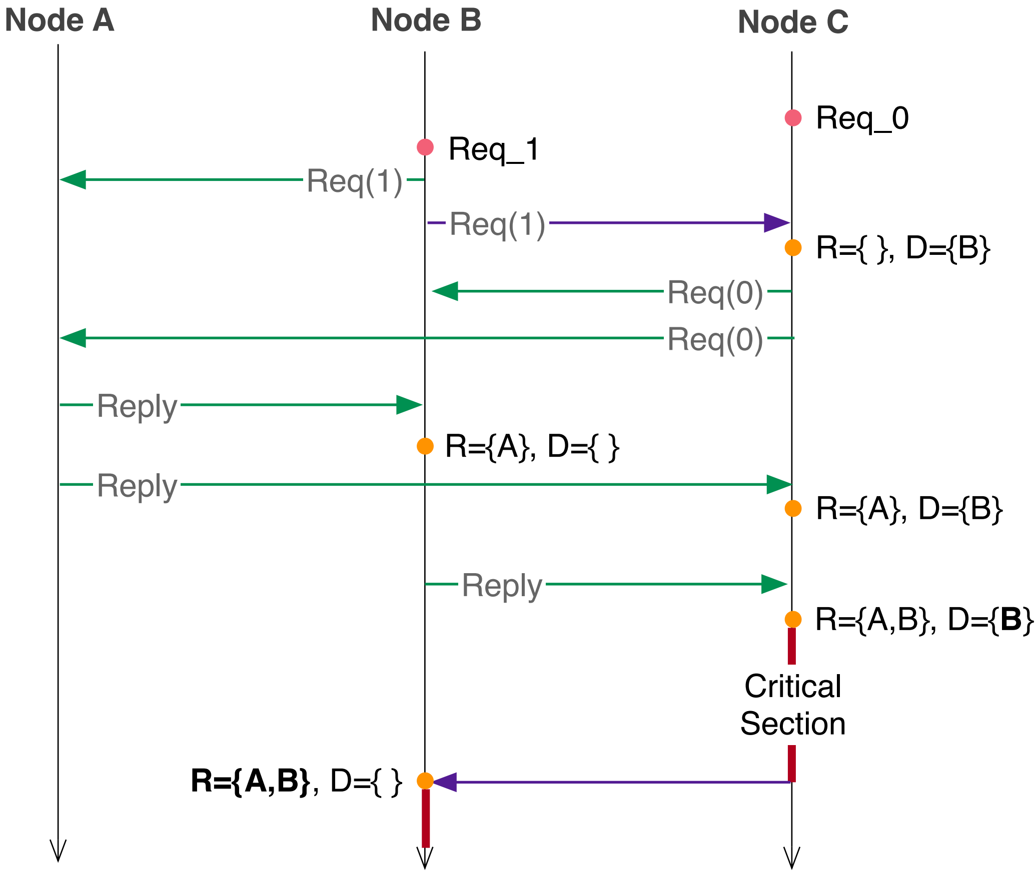
4/6 Ricart-Agrawala close-up



5/6 Ricart-Agrawala close-up



6/6 Ricart-Agrawala close-up



Ricart and Agrawala safety

- Suppose request T_1 is earlier than T_2.
- Consider how the process for T_2 collects its reply from process for T_1
    - T_1 must have already been time-stamped when request T_2 was received, otherwise the Lamport clock would have been advanced past time T_2
    - But then the process must have delayed reply to T_2 until after request T_1 exited the critical section. Therefore T_2 will not conflict with T_1.

Ricart and Agrawala overview

- Advantages:
  - Fair
  - Short synchronization delay
- Disadvantages
  - Very unreliable
  - *2(N-1)* messages for each entry/exit