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Exo: Atomic Broadcast for the Rack-Scale Computer

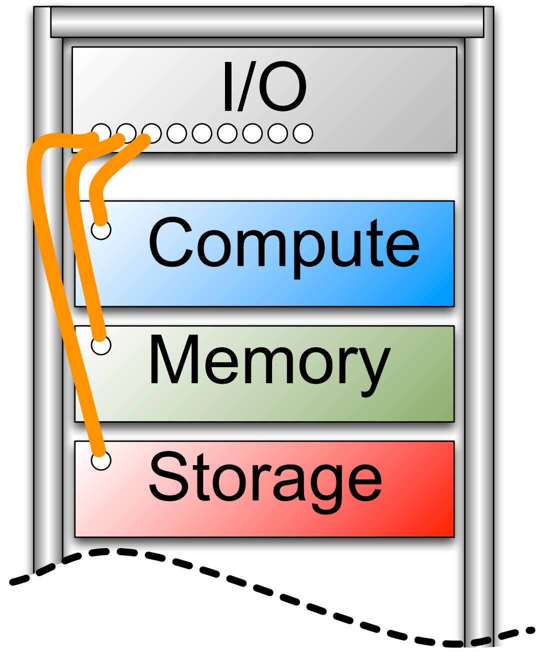
Matthew P. Grosvenor Marwan Fayed Andrew W. Moore

What is a Rack-Scale Computer

Today

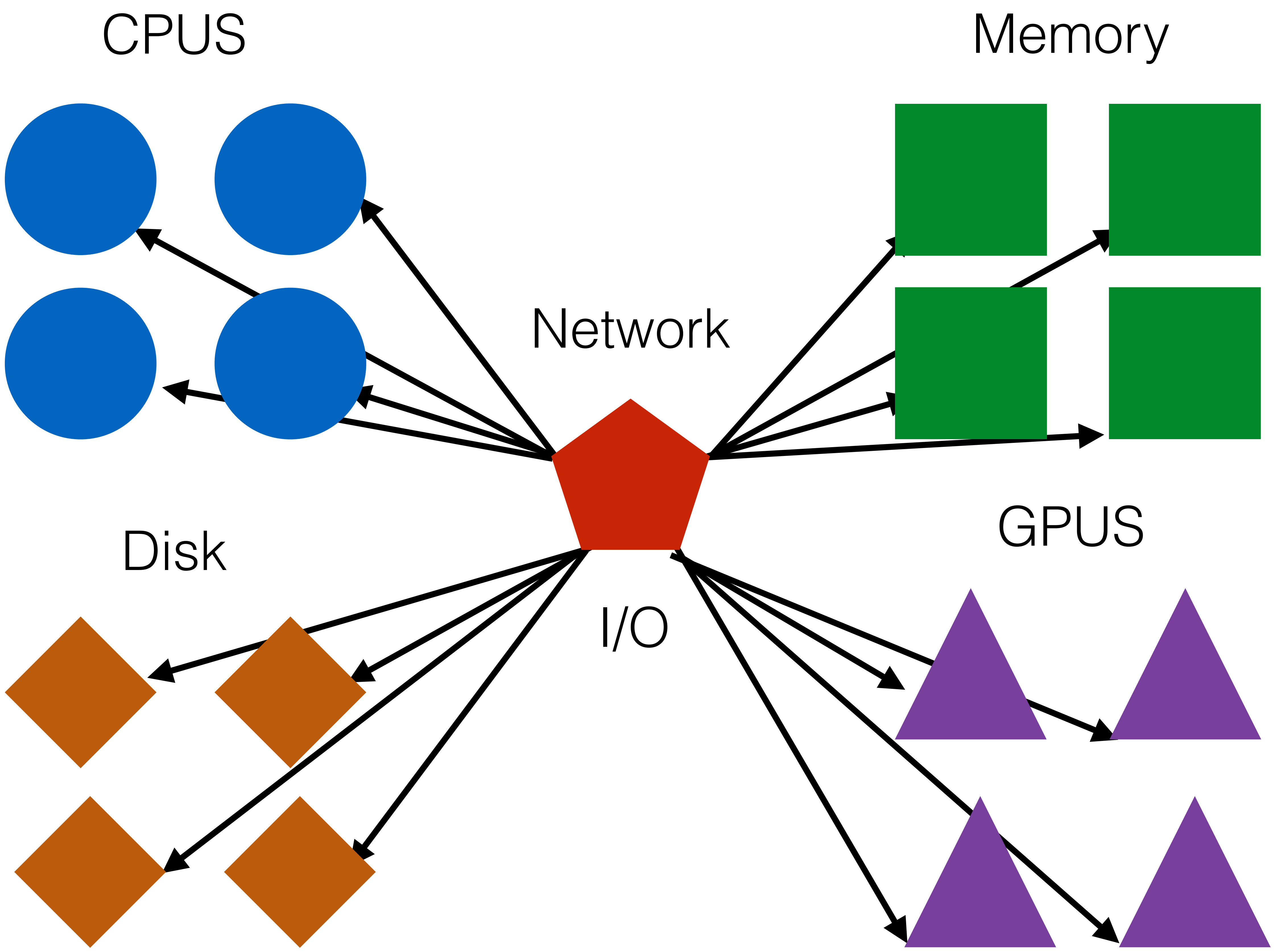
- 50 - 200 machines
- Commodity hardware
- Commodity network

Tomorrow



- 500-2000 “nodes”
- Disaggregated hardware
- Custom (photonic?) interconnect(s)

The problem with disaggregation



Other Types of Coordination

Single Machines

- Coordination using simple MESI/MOSI protocols
- Specialised hardware over a reliable, low latency interconnect.

✓ High performance

X Not failure tolerant

X Doesn't scale well

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Cluster Systems

- Coordination using software protocols
- General purpose, high latency, error prone network

X Low performance

✓ Fault Tolerant

X Doesn't scale well

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Something in the middle ???

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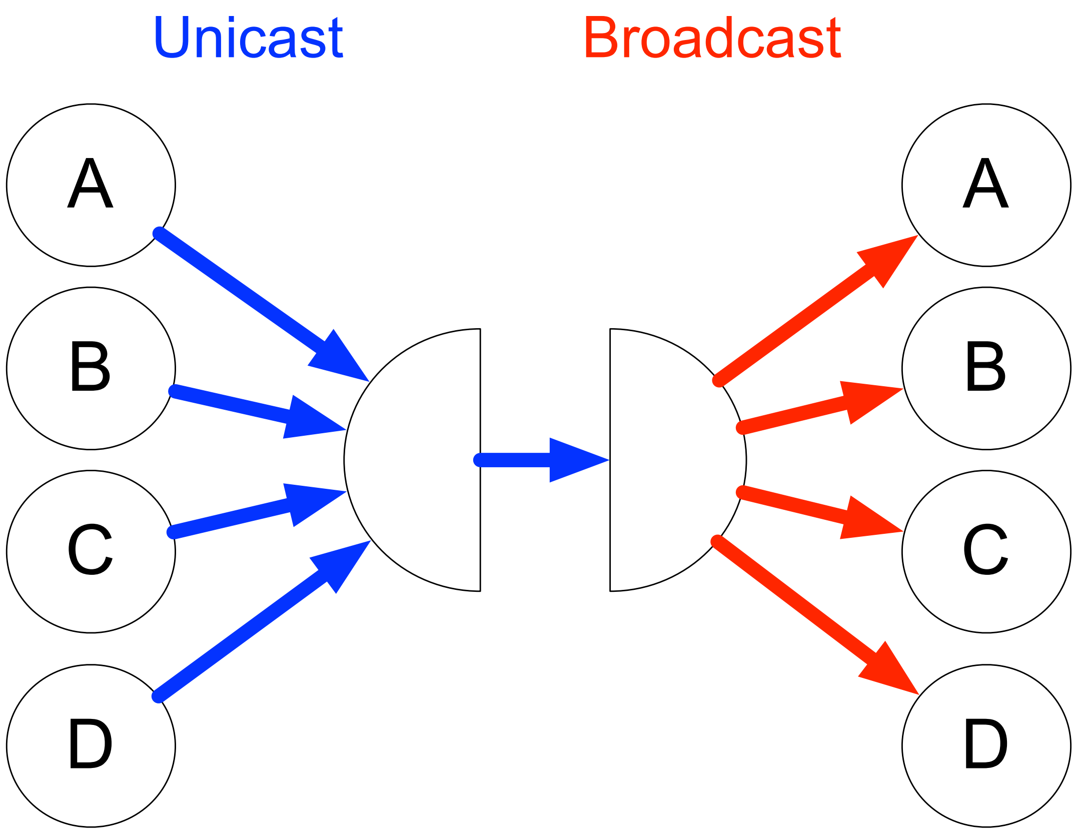
That scales?

Building a Coordination Network (Tomorrow)

- ✓ Silicon Photonic Interfaces on chip
- X High radix optical switches?
- ✓ Burst mode transceivers
- ✓ Passive all optical interconnect (PON)
- ✓ Network broadcast as a primitive for building Atomic Broadcast



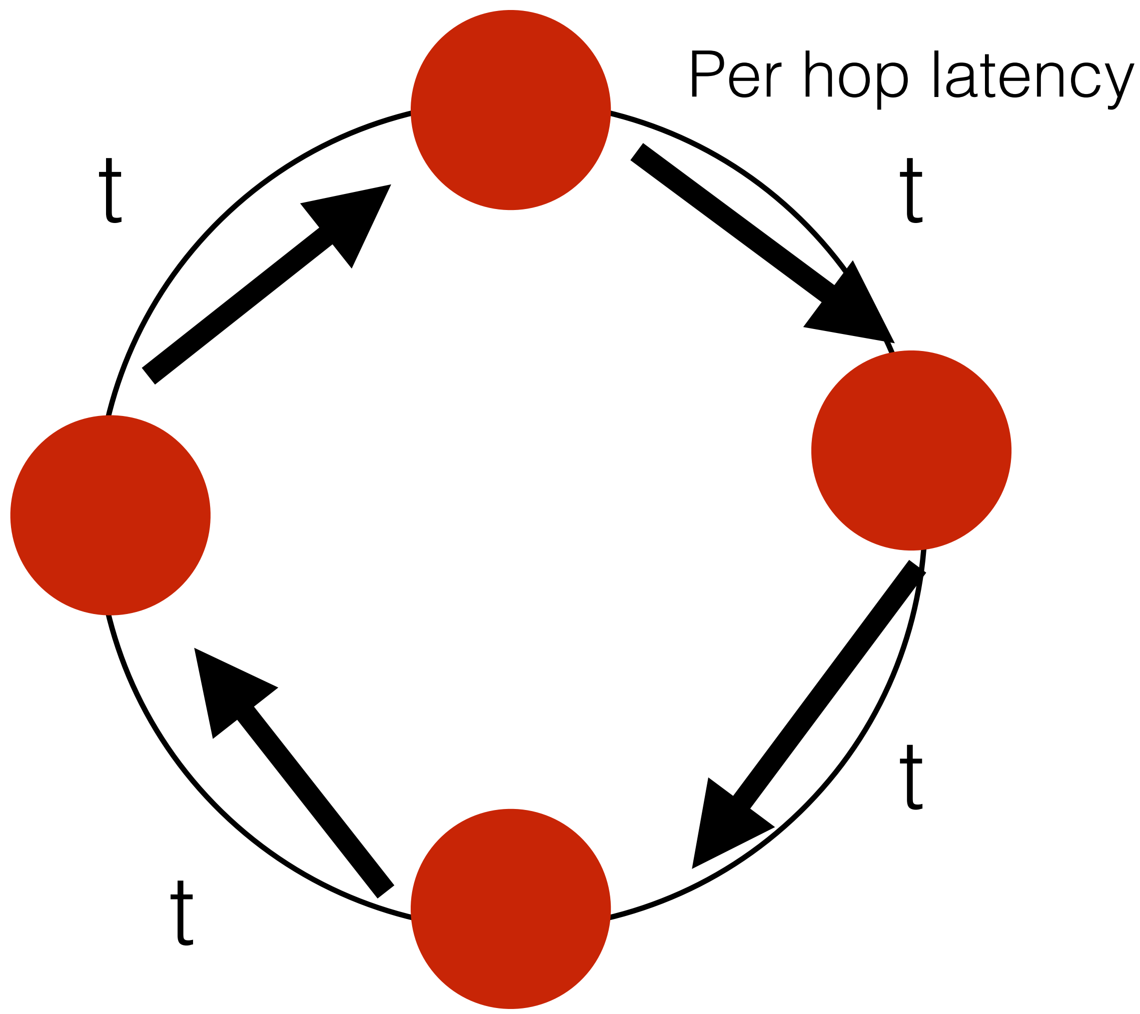
Media Access and Agreement

- How do we mediate access to the network?
- What agreement protocol do we use?

- Use token rings
    - Two birds with one stone
        - ✓ Well established MAC protocol
        - ✓ Well established agreement protocol. Very high (optimal) throughput performance.

The Problem with Token Passing

- Token passing is latency bound
- Each host must wait at least n-1 hops for agreement = n x per-hop latency (t)
- Per hop latency must be minimised

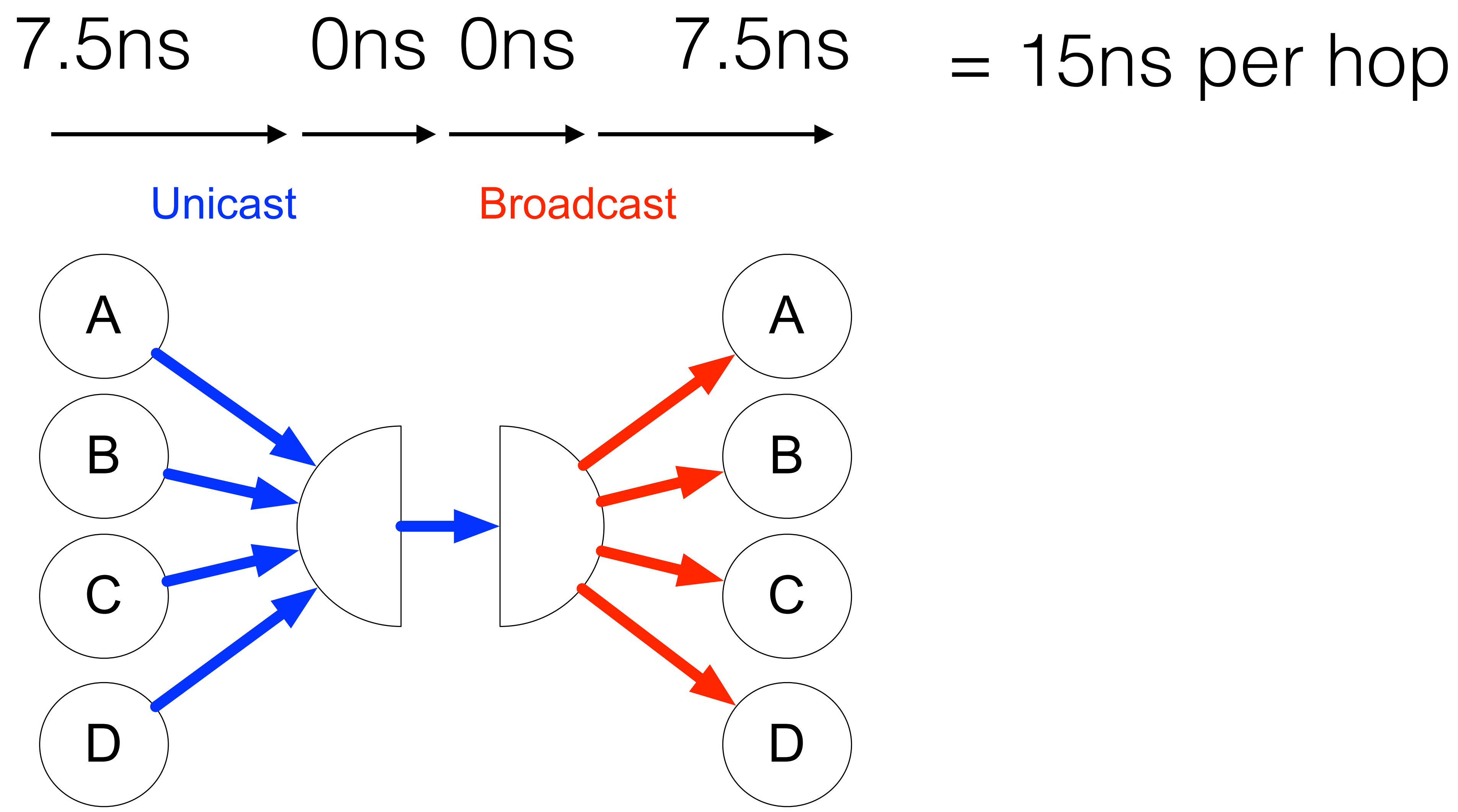


Total latency = t + t + t + t = 4t

Throughput (per host) ≈ 1/ 4t

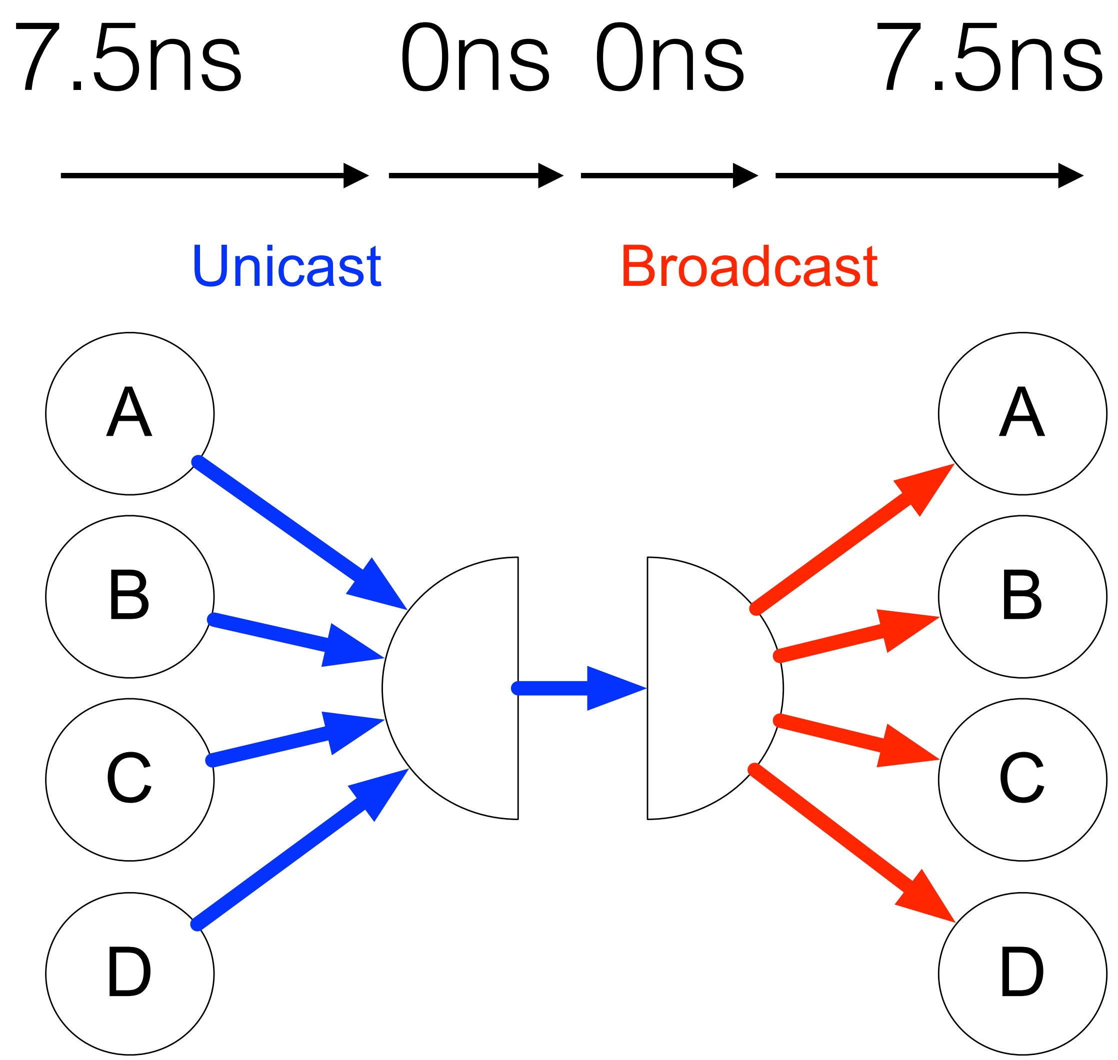
What's the latency?

Assuming 3m of fibre @ 0.75C



What's the latency?

Assuming 3m of fibre @ 0.75C



= 15ns per hop

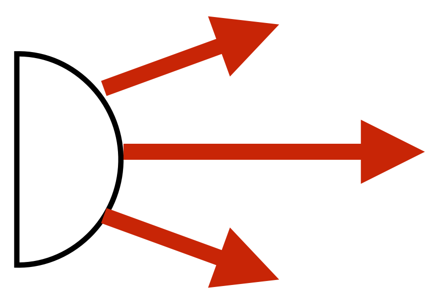
@10G 64B frames

= 14.4M msg/sec

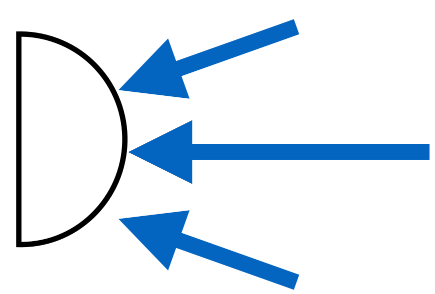
Building a Coordination Network (Today)

Use Exalink Fusion Switch to emulate all optical network

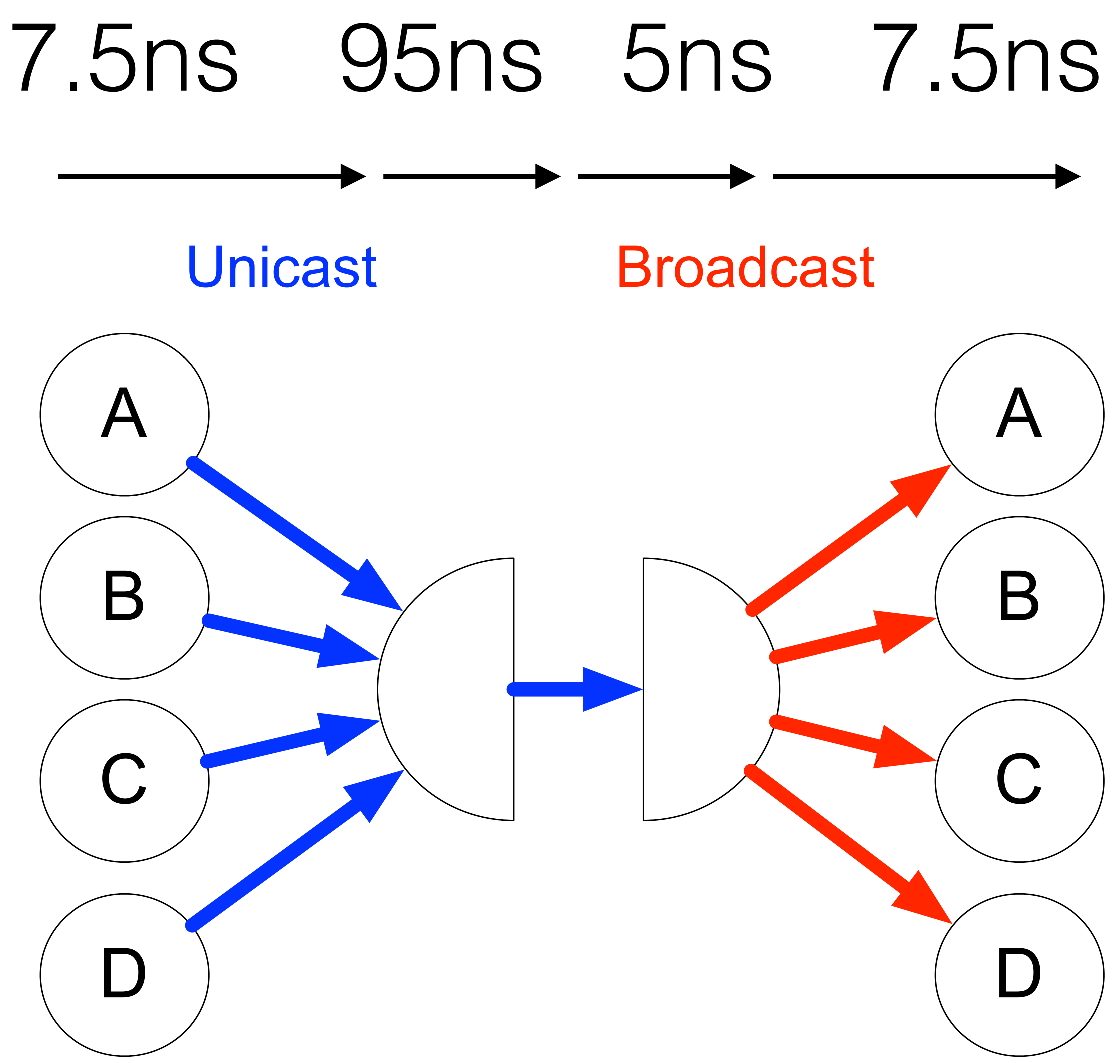
- Broadcast - 5ns



- Aggregation - 95ns



Building a Coordination Network (Today)



= 115ns per hop

= 8.6M msg/sec

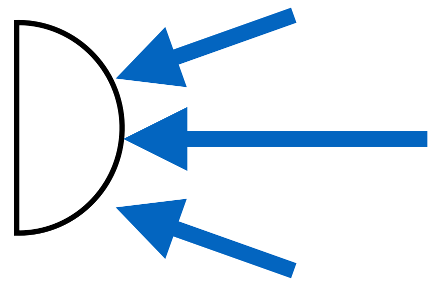
Fusion Aggregate

Fusion Broadcast

Building a Coordination Network (In the lab)

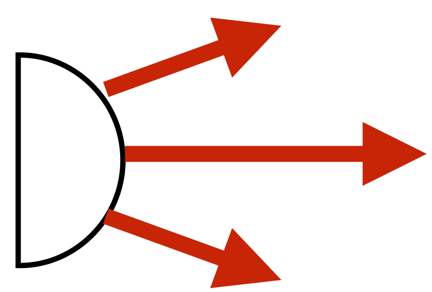
- Use ethernet switch and matrix switch to emulate Exablaze Fusion

- Arista 7124FX



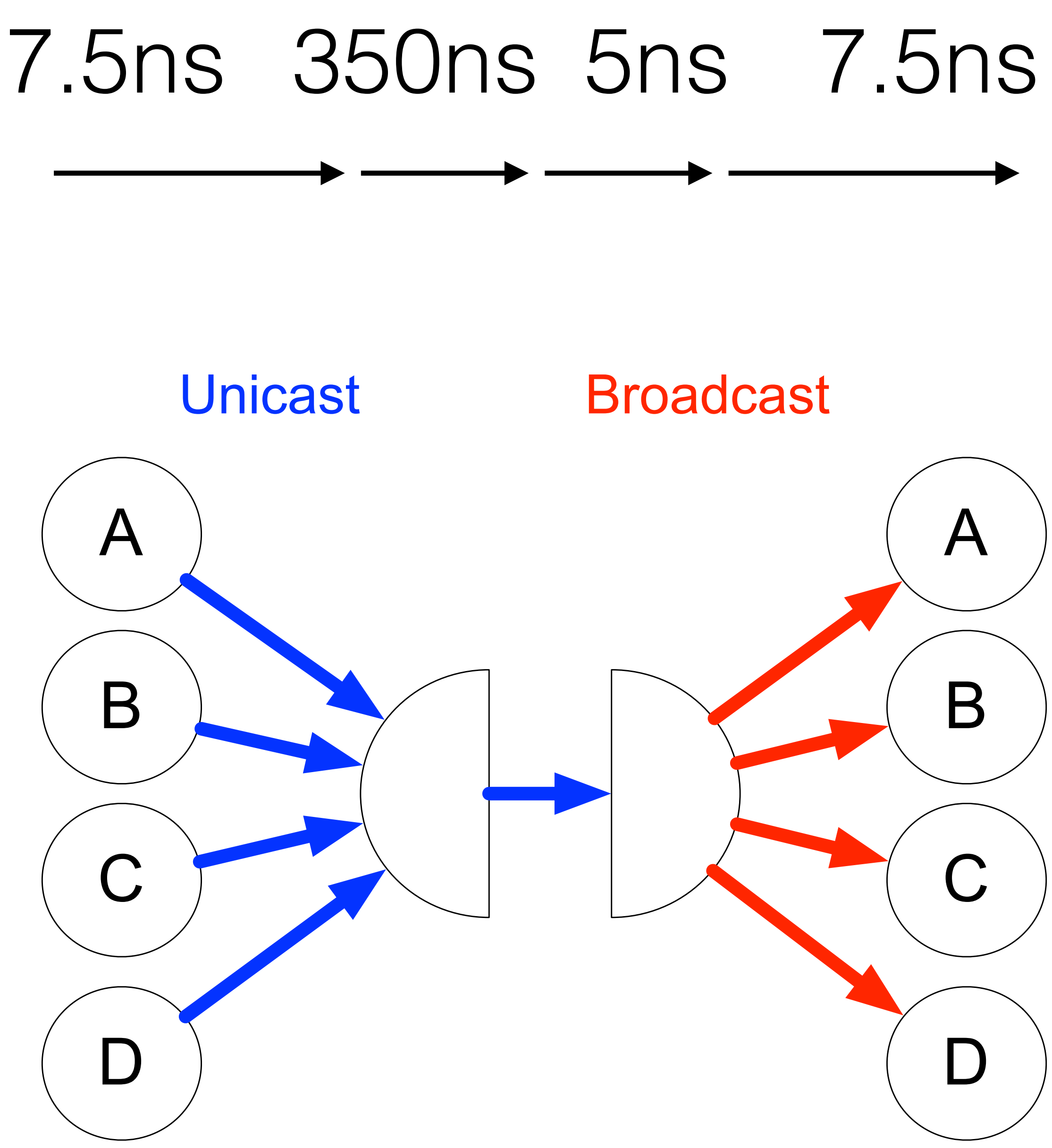
  - Aggregation/switching 350ns

- Exablaze ExaLink 50



  - Broadcast <5ns

Building a Coordination Network (in the lab)



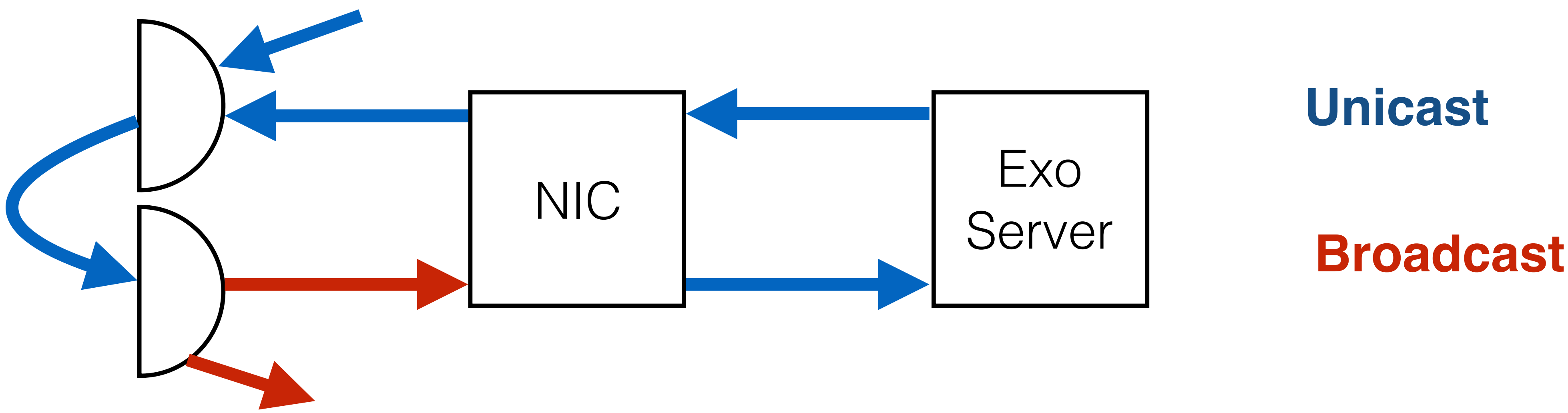
= 370ns per hop

= 2.7M msg/sec

Artist 7124FX

Exablaxe ExaLink50

But wait, there's more… (latency)



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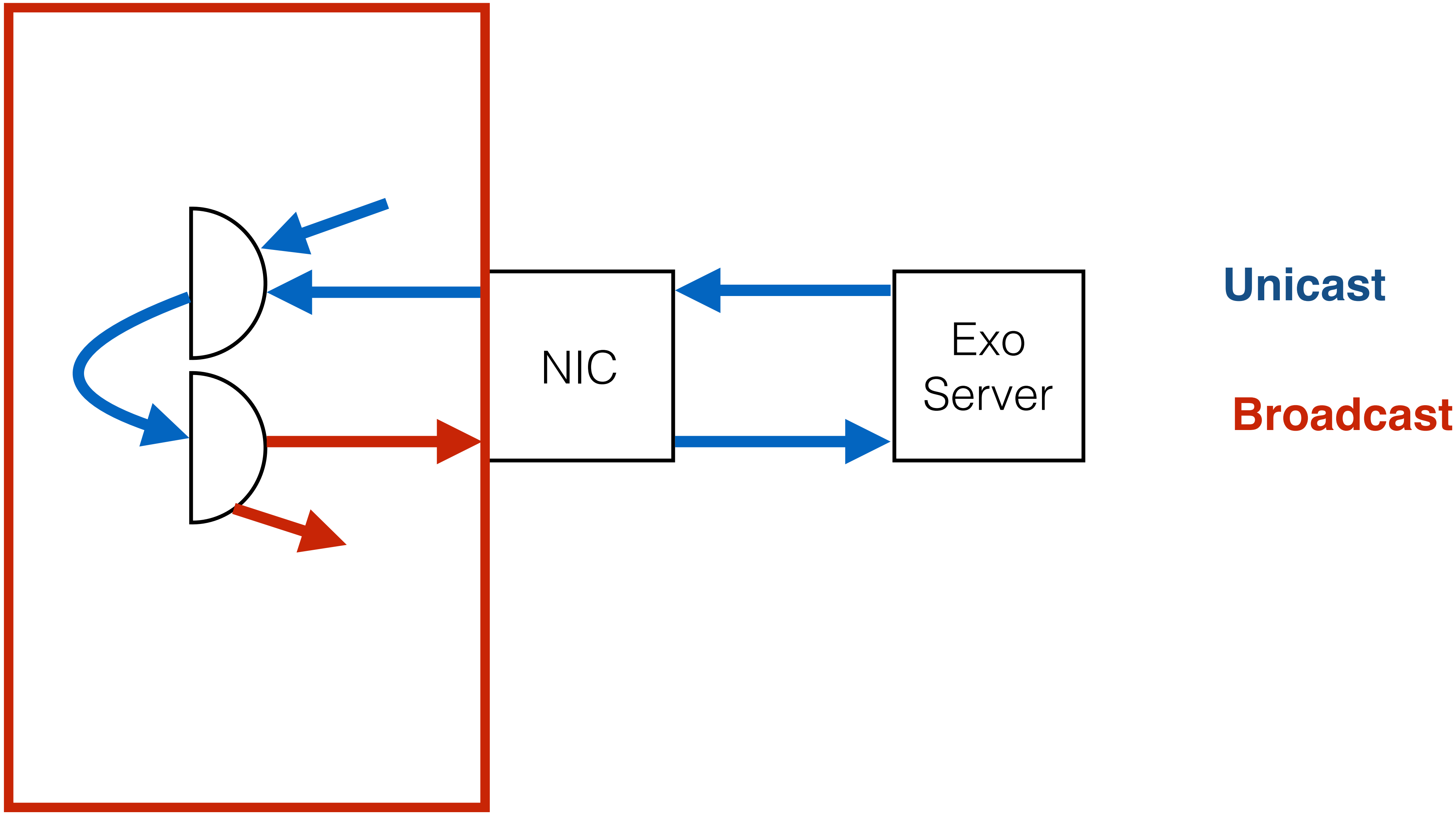
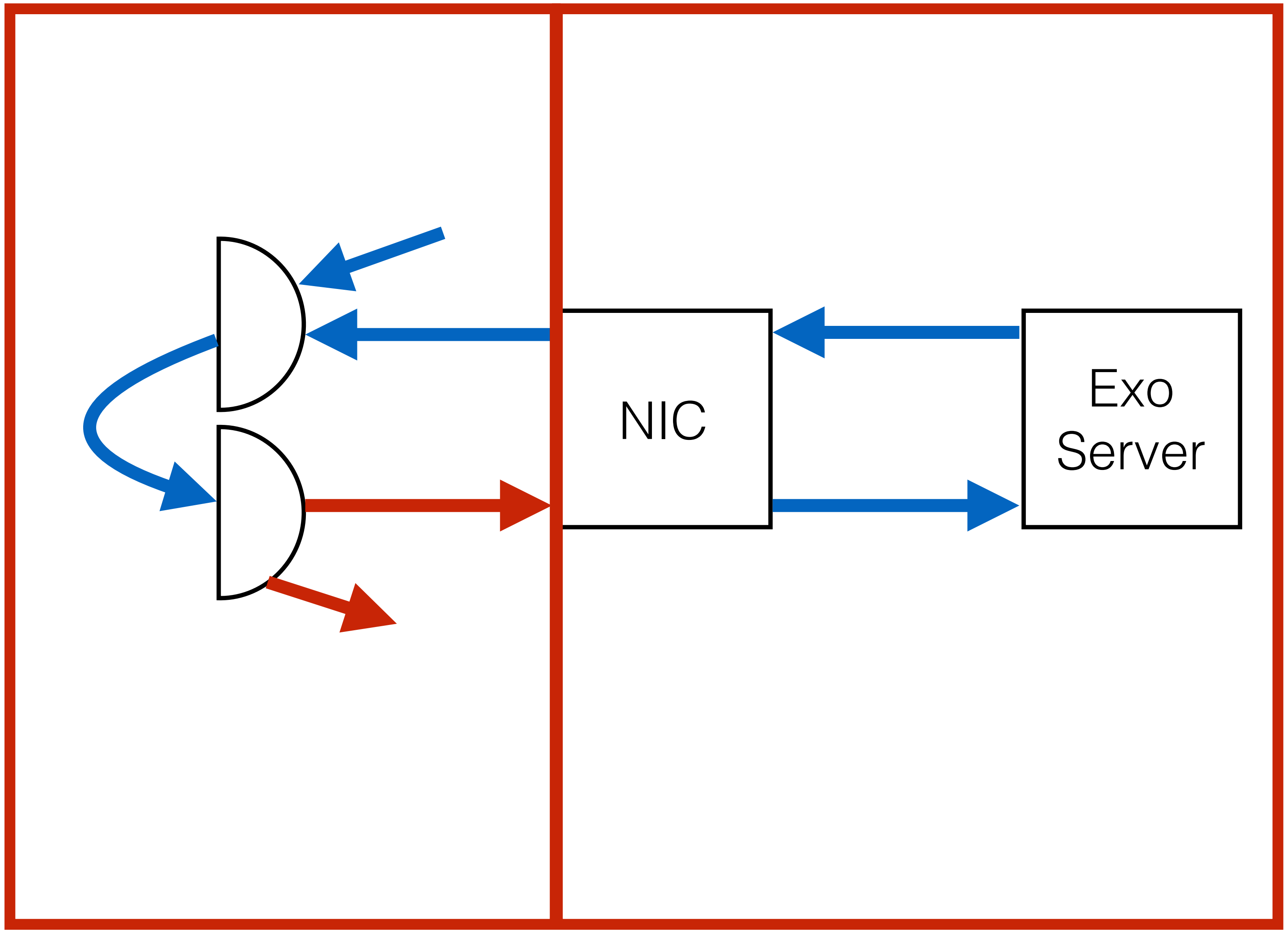


Network Latency

370ns

But wait, there's more (latency)



Unicast

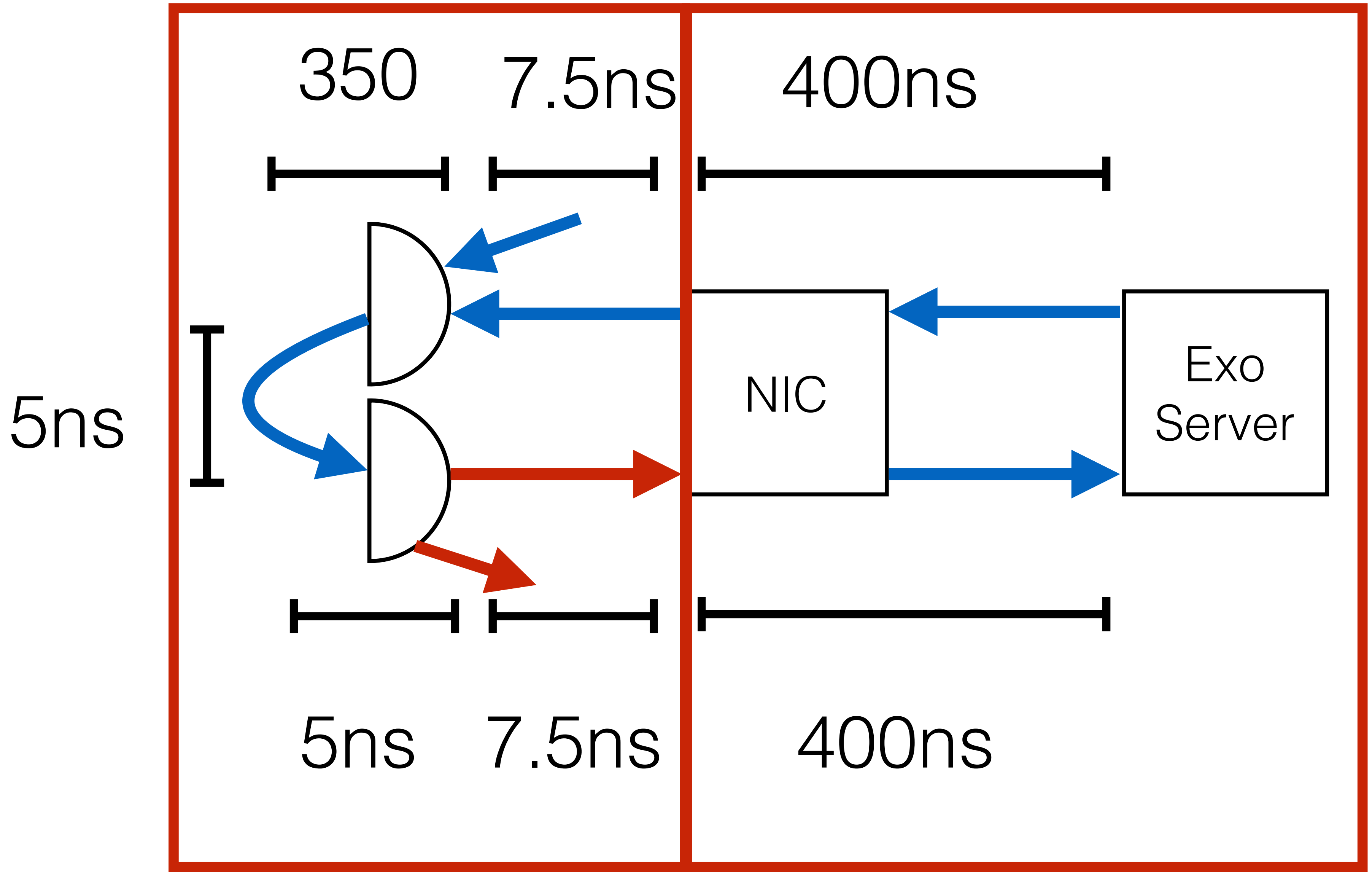
Broadcast

Network Latency

PCIe Latency

370ns

But wait, there's more… (latency)



Unicast

Broadcast

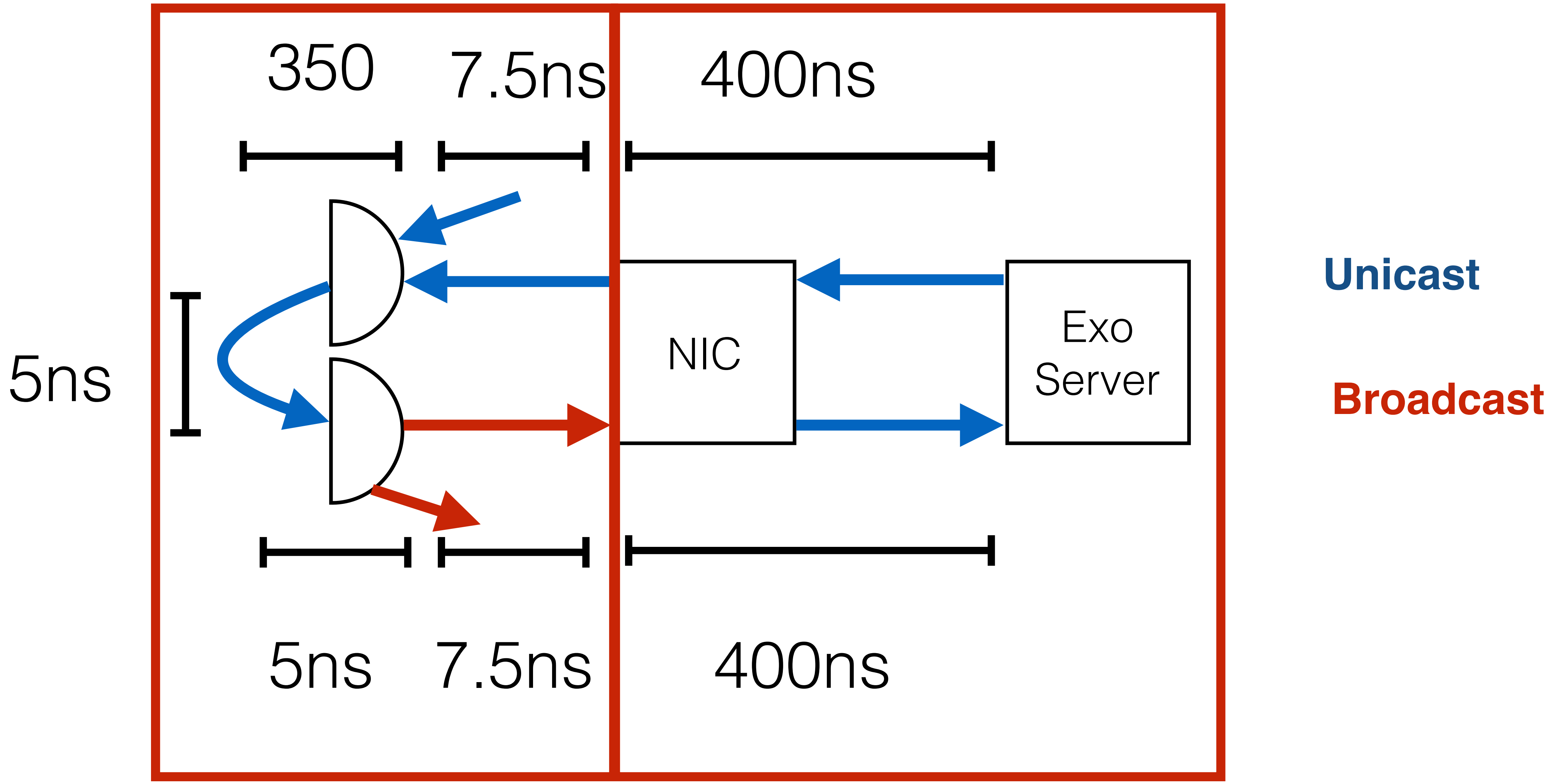
Network Latency

370ns

PCIe Latency

>800ns

But wait, there's more… (latency)



- total per-hop-latency ≈ 1us
- 200 x 1us ≈ 200us
  ≈ 5000 msgs per host per second.

Dealing with latency

1. Make it go away
   - e.g use a Fusion
   - e.g use all optical

2. Hide it
   - Introduce pipelining

Dealing with latency

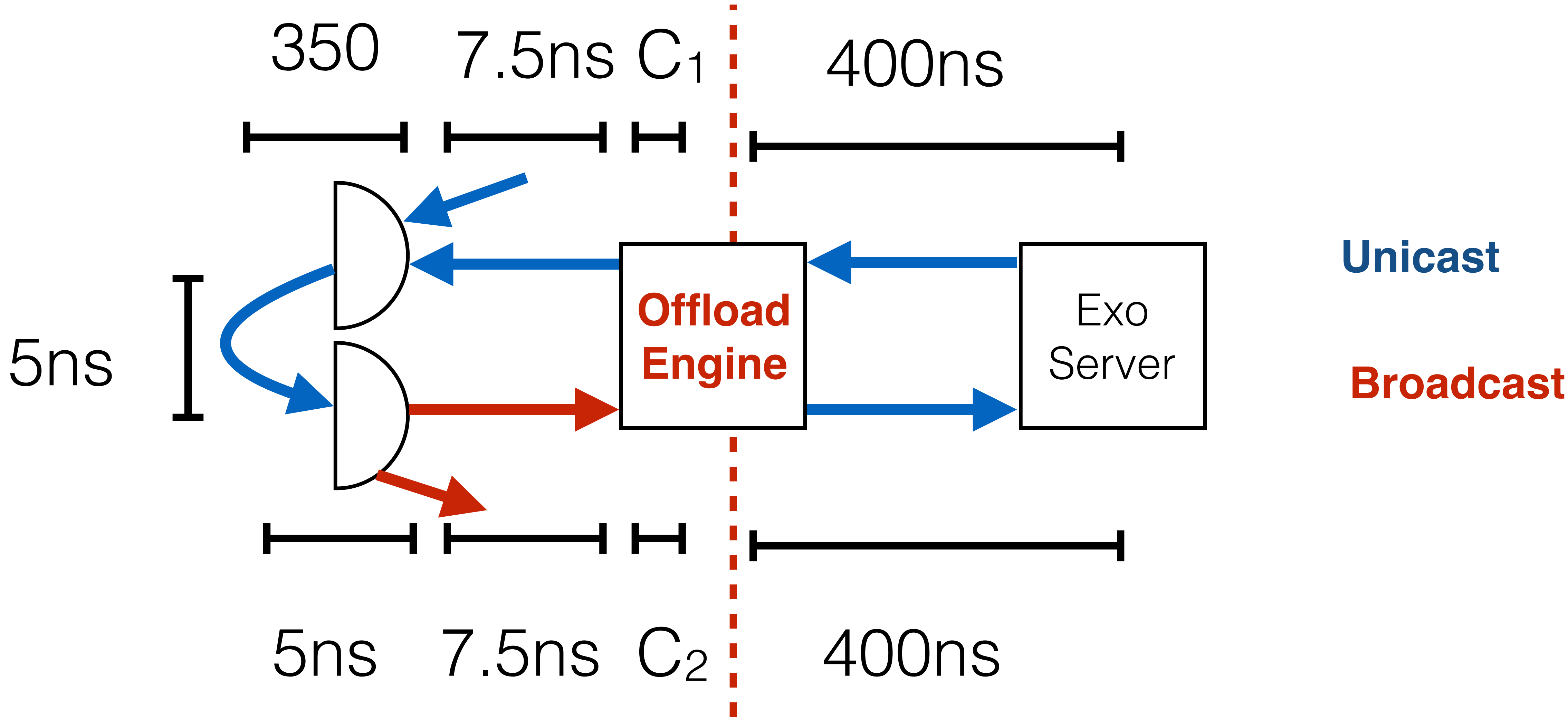
1. Make it go away

   - e.g use a Fusion
   - e.g use all optical

2. **Hide it**

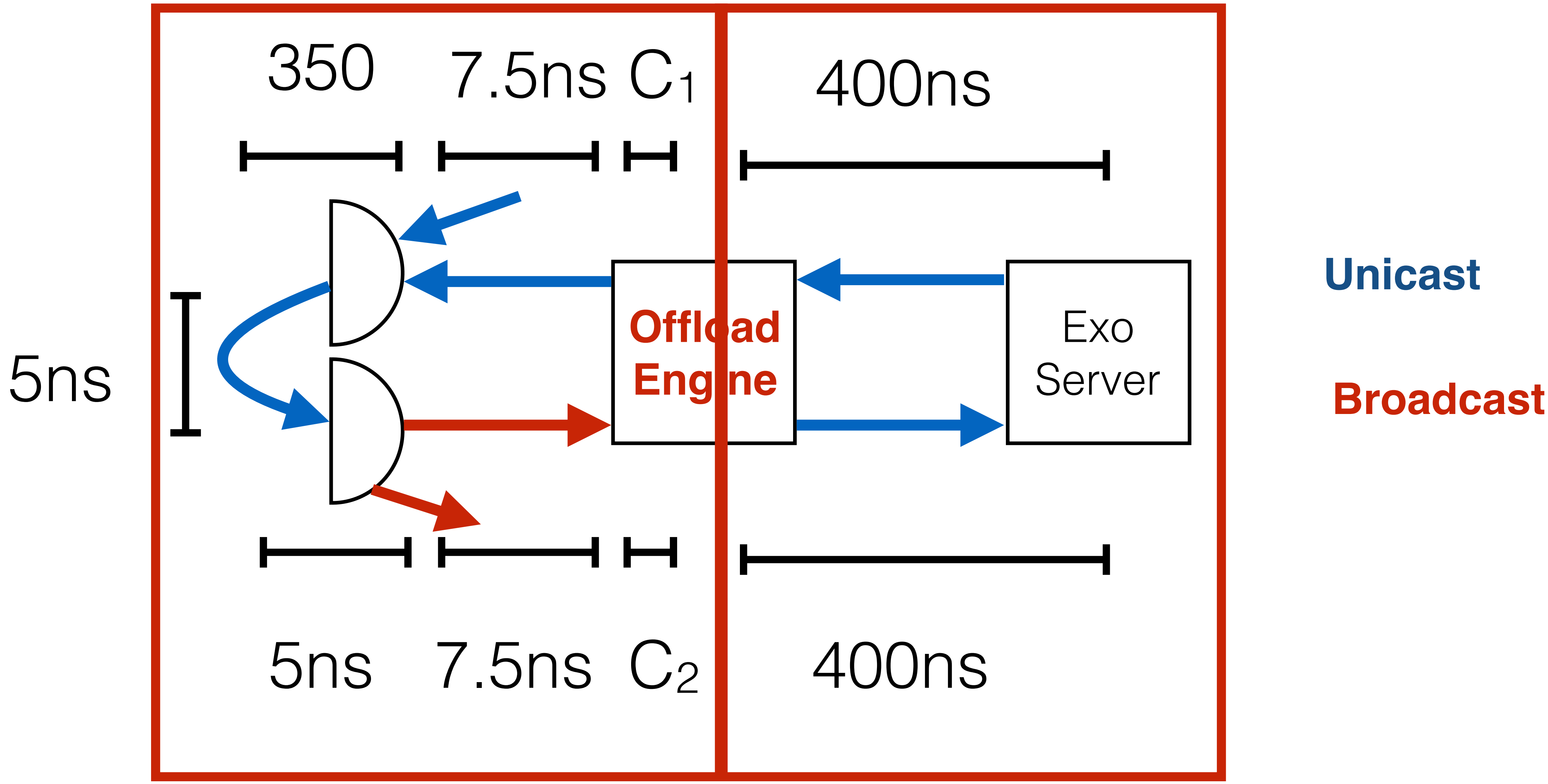
   - **Introduce pipelining**

Hiding Latency



- Introduce pipelining to hide latency
  - Host to NIC and NIC to network transmissions run in parallel

Hiding Latency



- In network latency ≈ 400ns
- Per-hop latency ≈ 1us (pipelined for 1 message per 400ns)
- 200 x 400ns ≈ 80us
  ≈ 12,500 messages per second / per host.

Let’s Talk About Failure

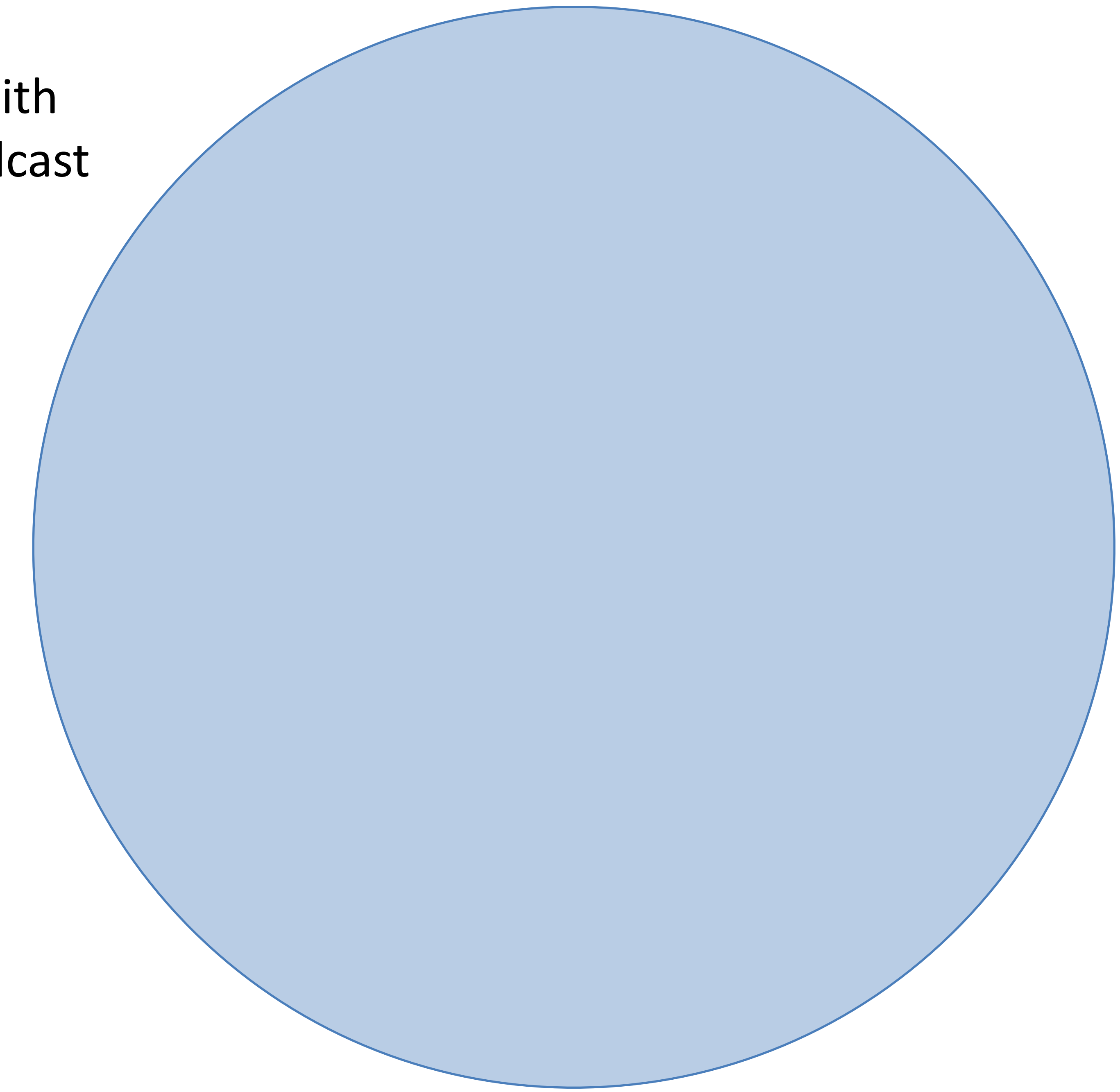
- Failure is very unlikely.
  - No packet loss due to congestion
  - Bit errors on the wire 1/10^12 … 1/10^14
  - Partitioning - Single chip? Can it half fail? Byzantine?
    - 1/10^20 ??
  - Partitioning - requires n-way x m - correlated failure
    - (1/10^12)^n * m
- Therefore, optimise for the common case

The Exo Protocol

- Protocol is implemented correctly on all hosts
- Hosts may stop, crash, restart, loose packets or become partitioned
- The is a fixed upper number of hosts (n) in the network. Host may leave and come back, but more hosts may not be added.

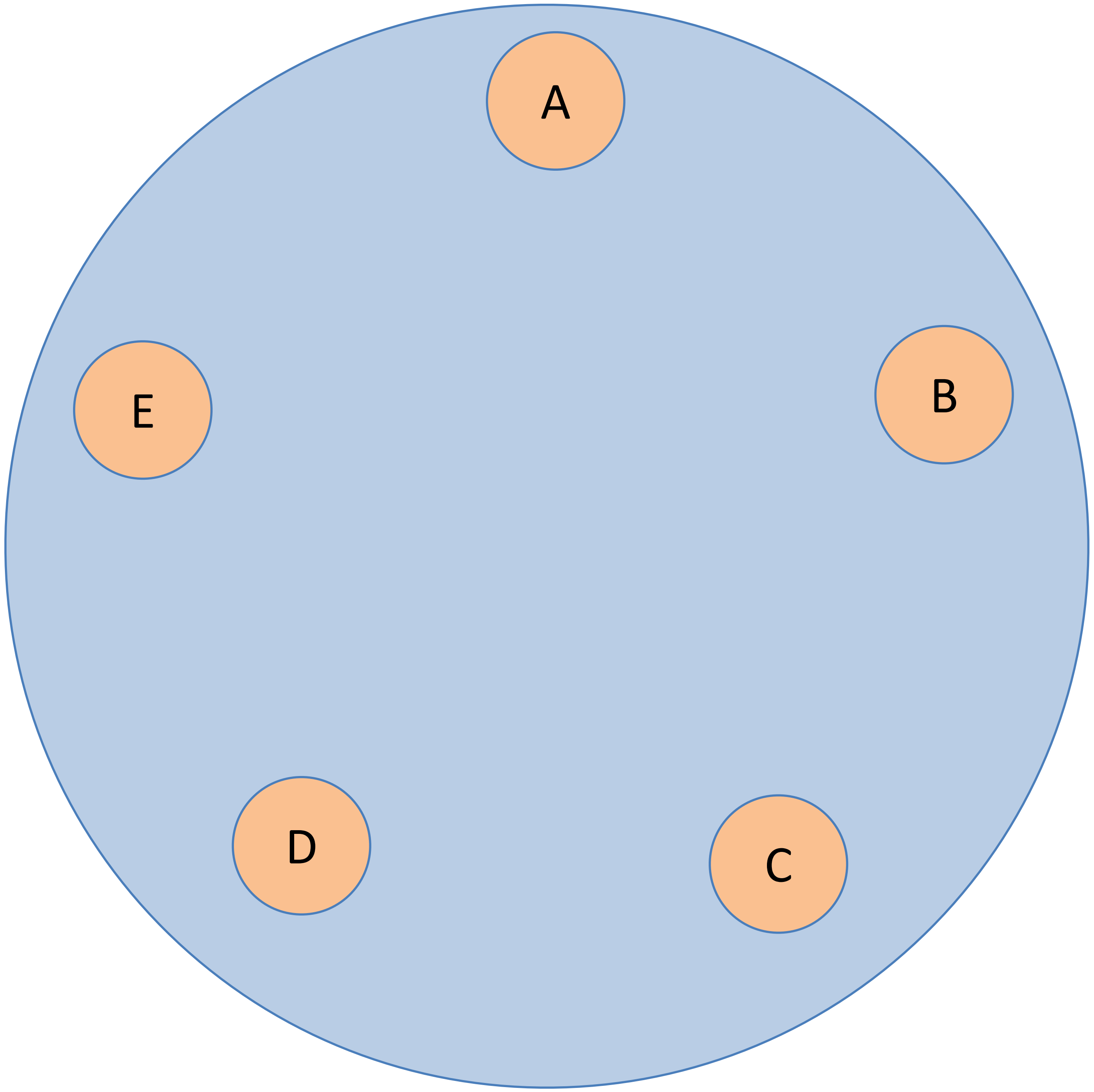
Anatomy of the Exo Protocol

Assume a network with fast and cheap broadcast messaging



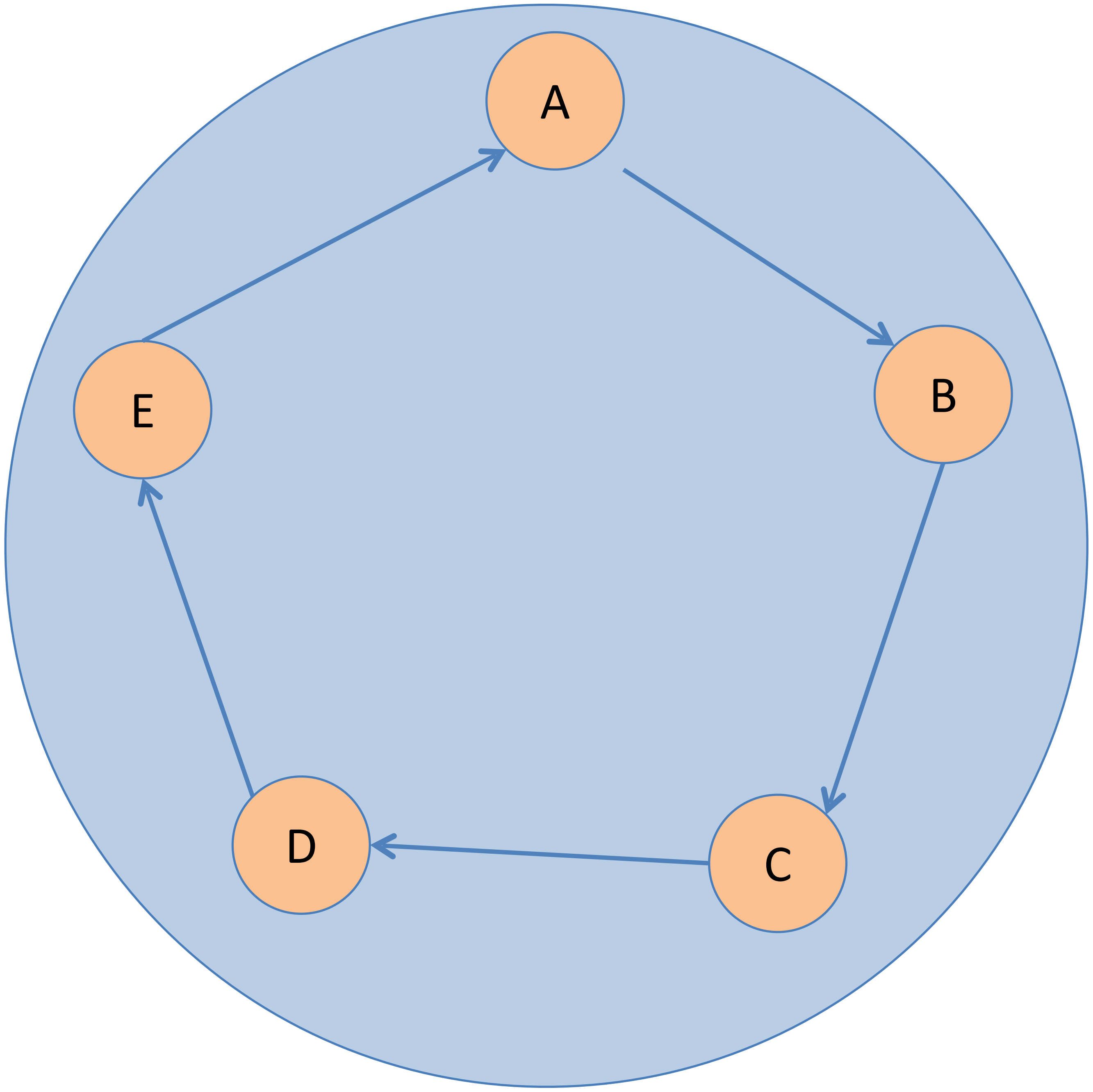
Anatomy of the Exo Protocol

And some maximum number of hosts ***n*** (5) labeled **A-E**



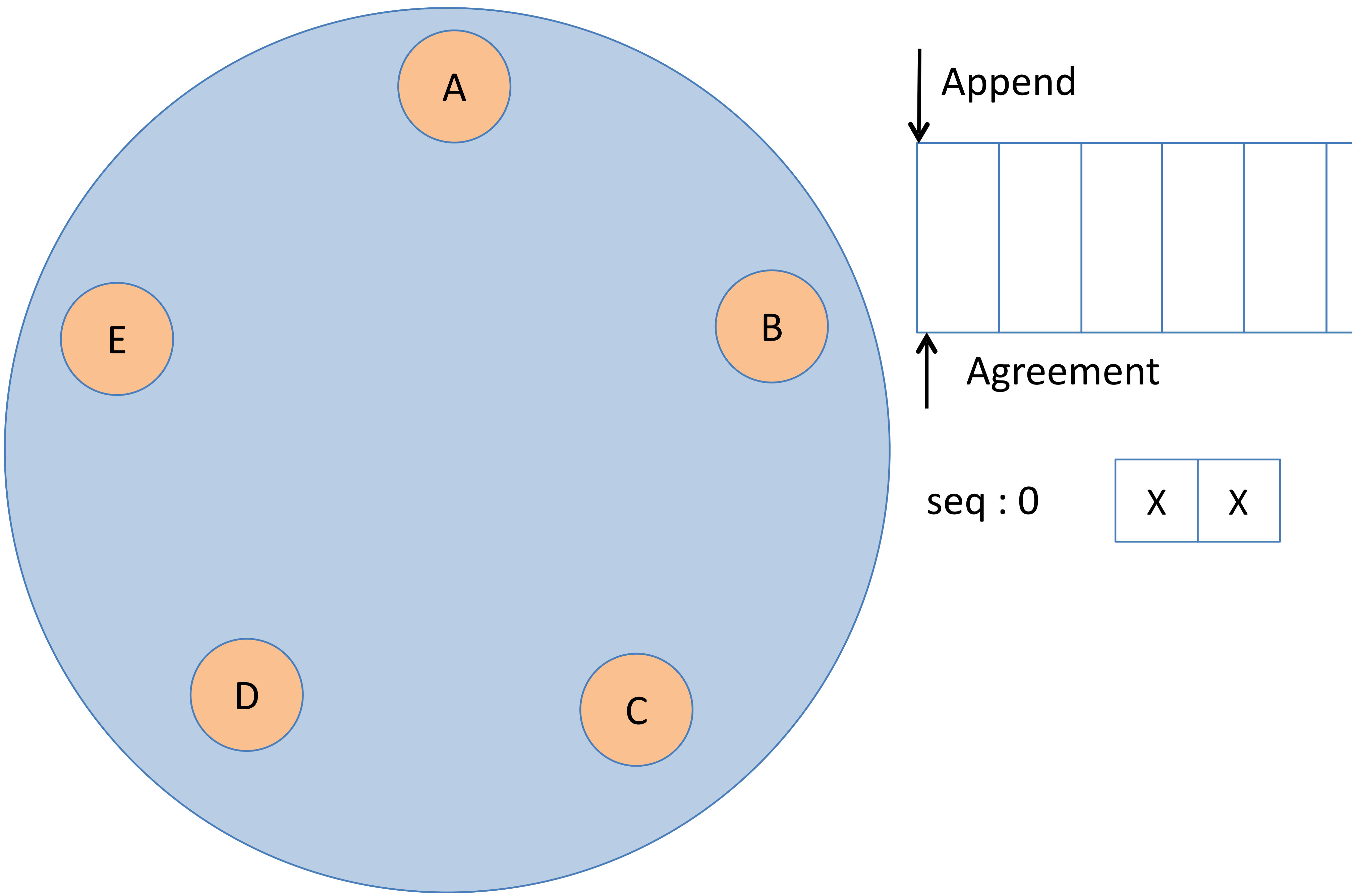
Anatomy of the Exo Protocol

And some maximum number of hosts ***n*** (5) labeled **A-E,** in a fixed, predetermined order



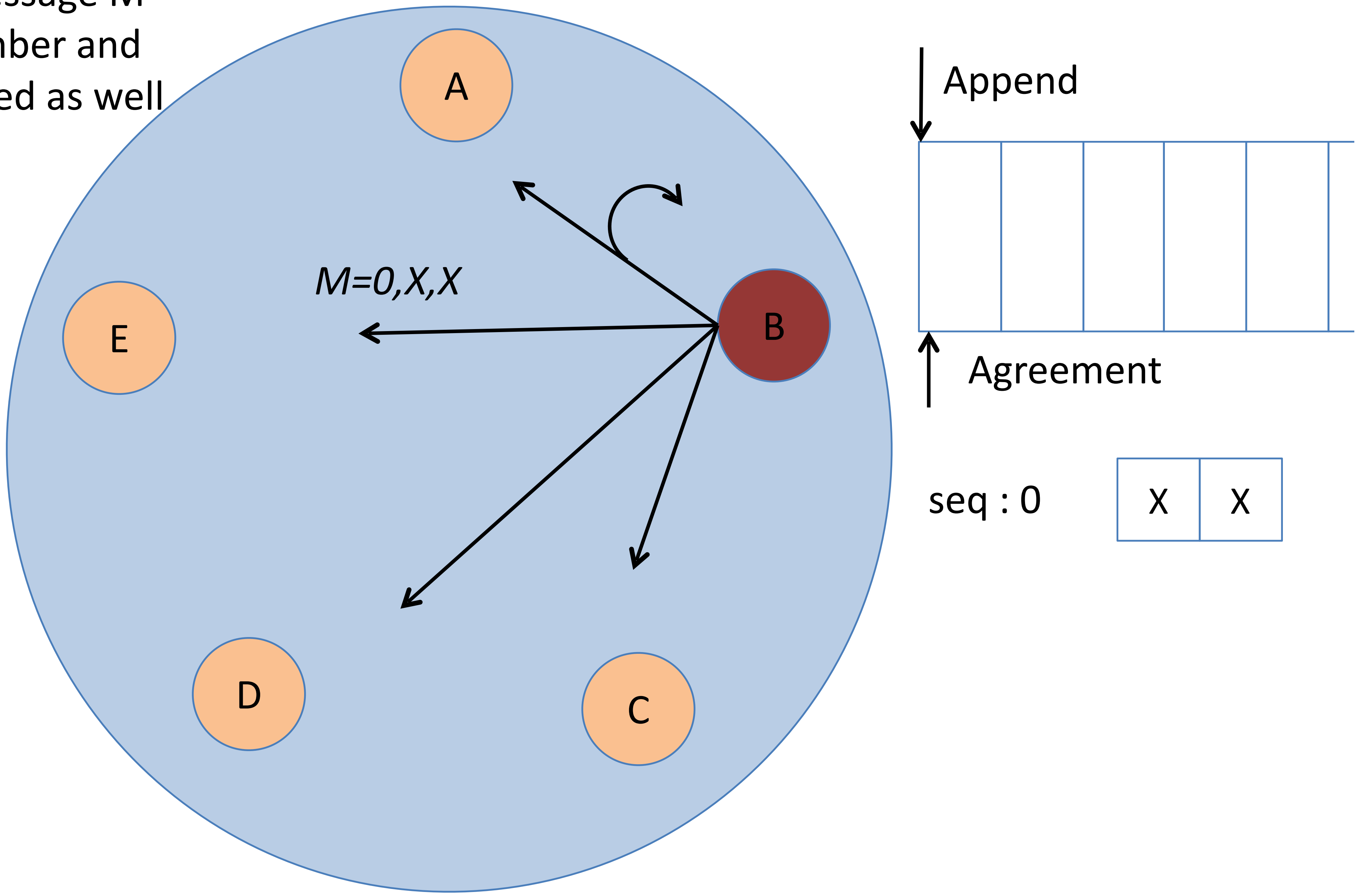
Anatomy of the Exo Protocol

Each host keeps the following state:
-append only log
-sequence number
-**n**/2 message history



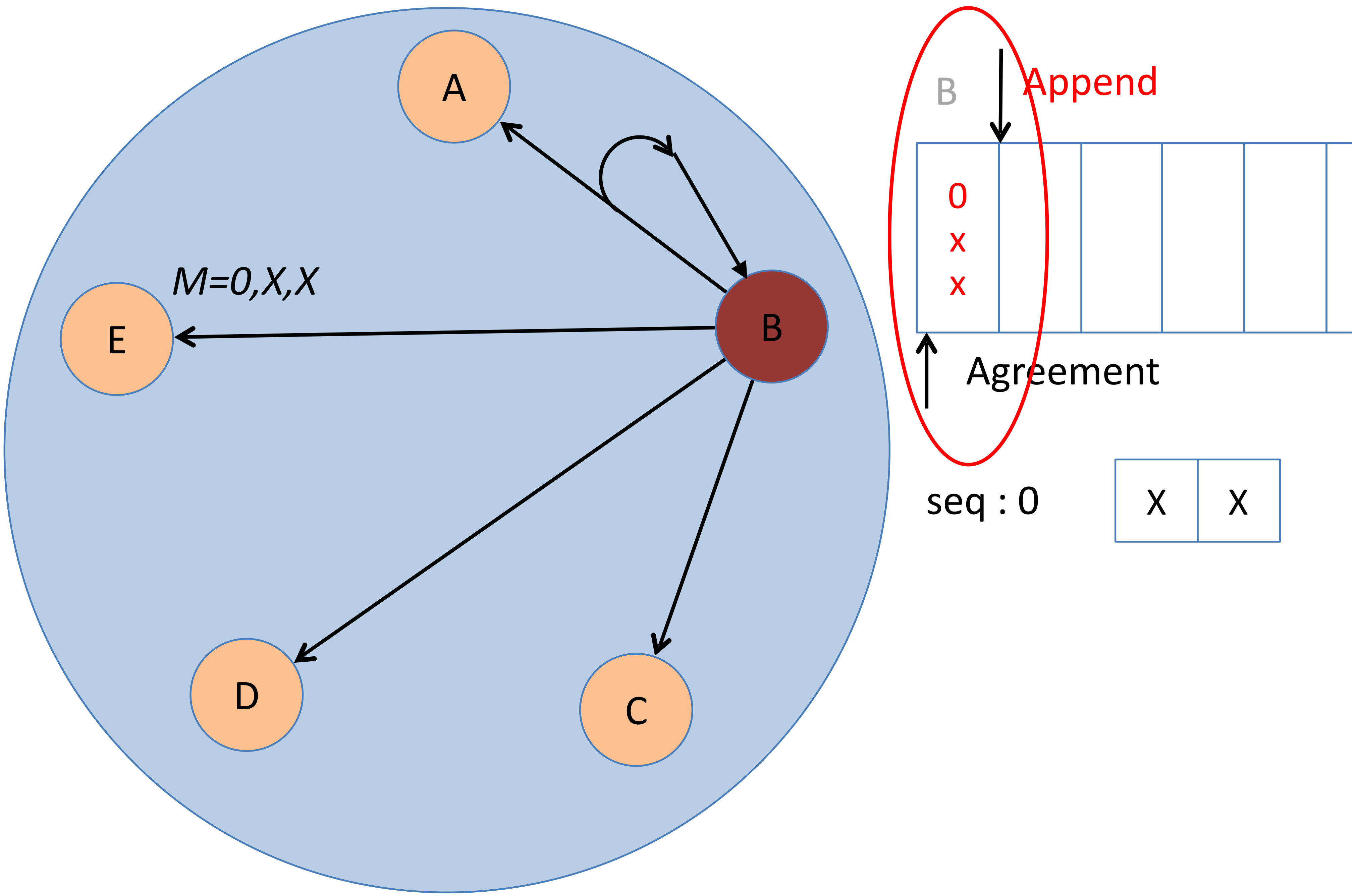
Anatomy of the Exo Protocol

Host *B* broadcasts a message M with the sequence number and message history included as well as any data (optional)



Anatomy of the Exo Protocol

Message from B arrives at all hosts, causes a:
-log append

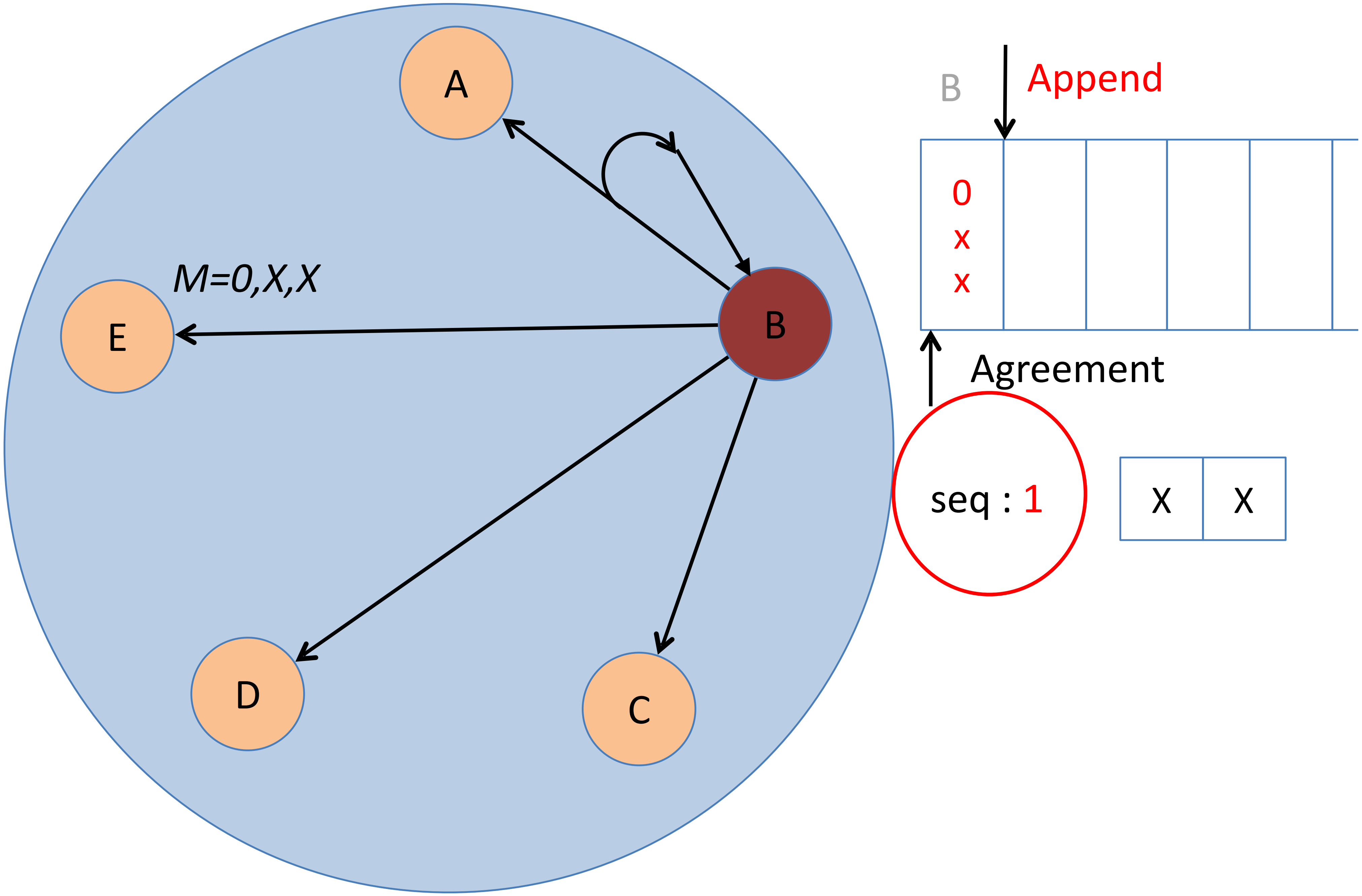


Anatomy of the Exo Protocol

Message from B arrives at all hosts, causes a:

-log append

-sequence number update



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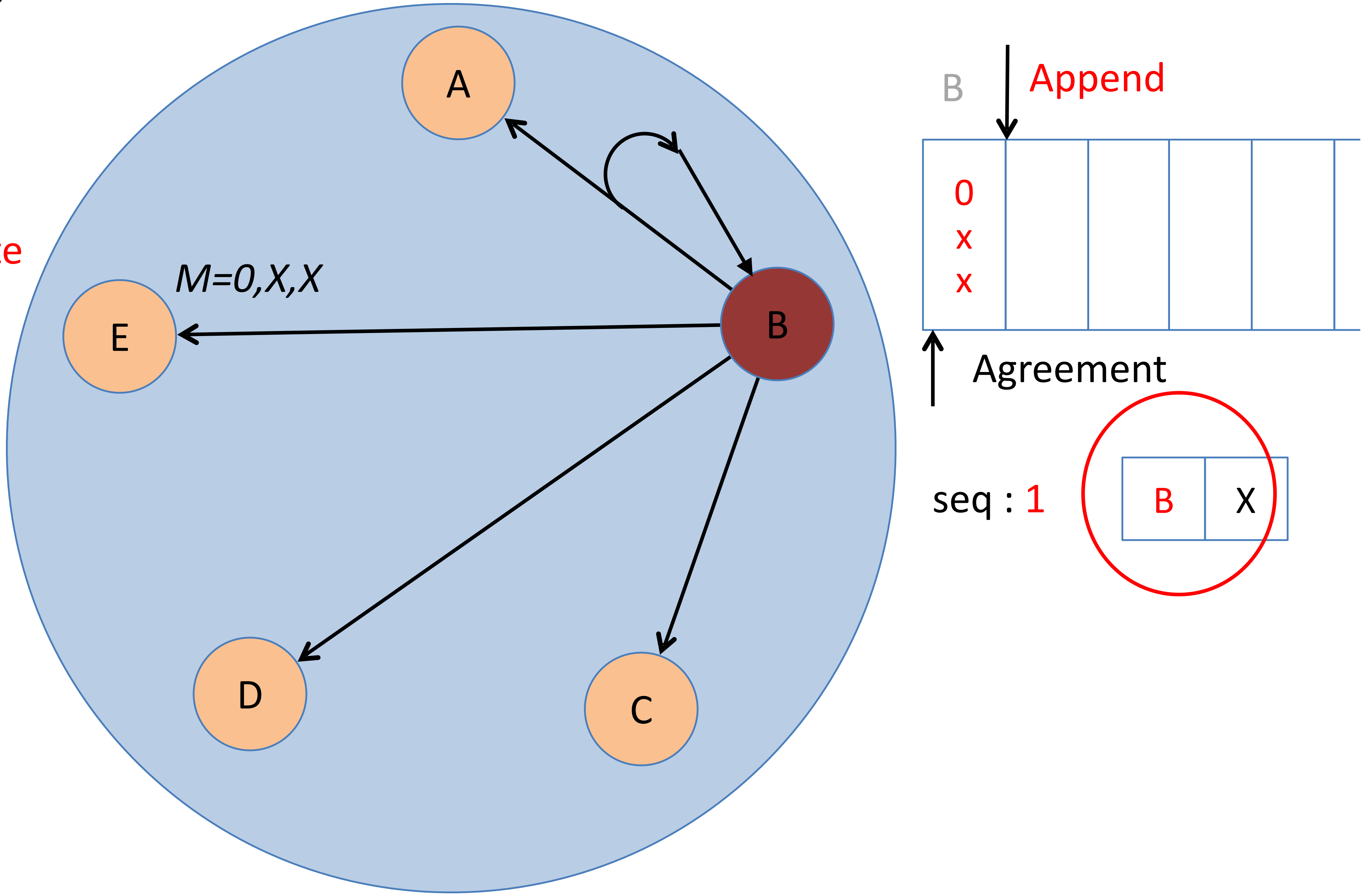
Message from B arrives at all hosts, causes a:

-log append

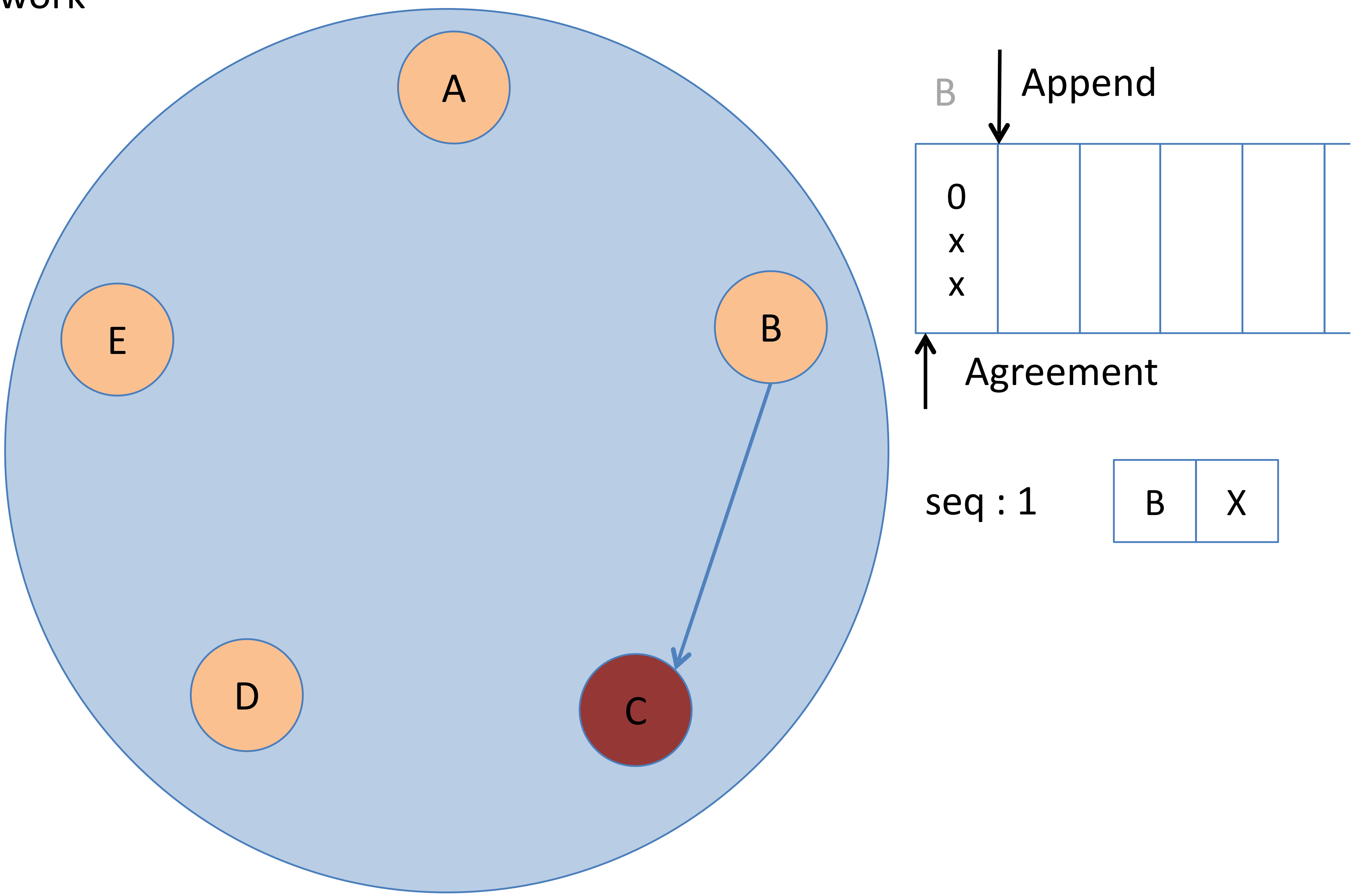
-sequence number update

-message history update



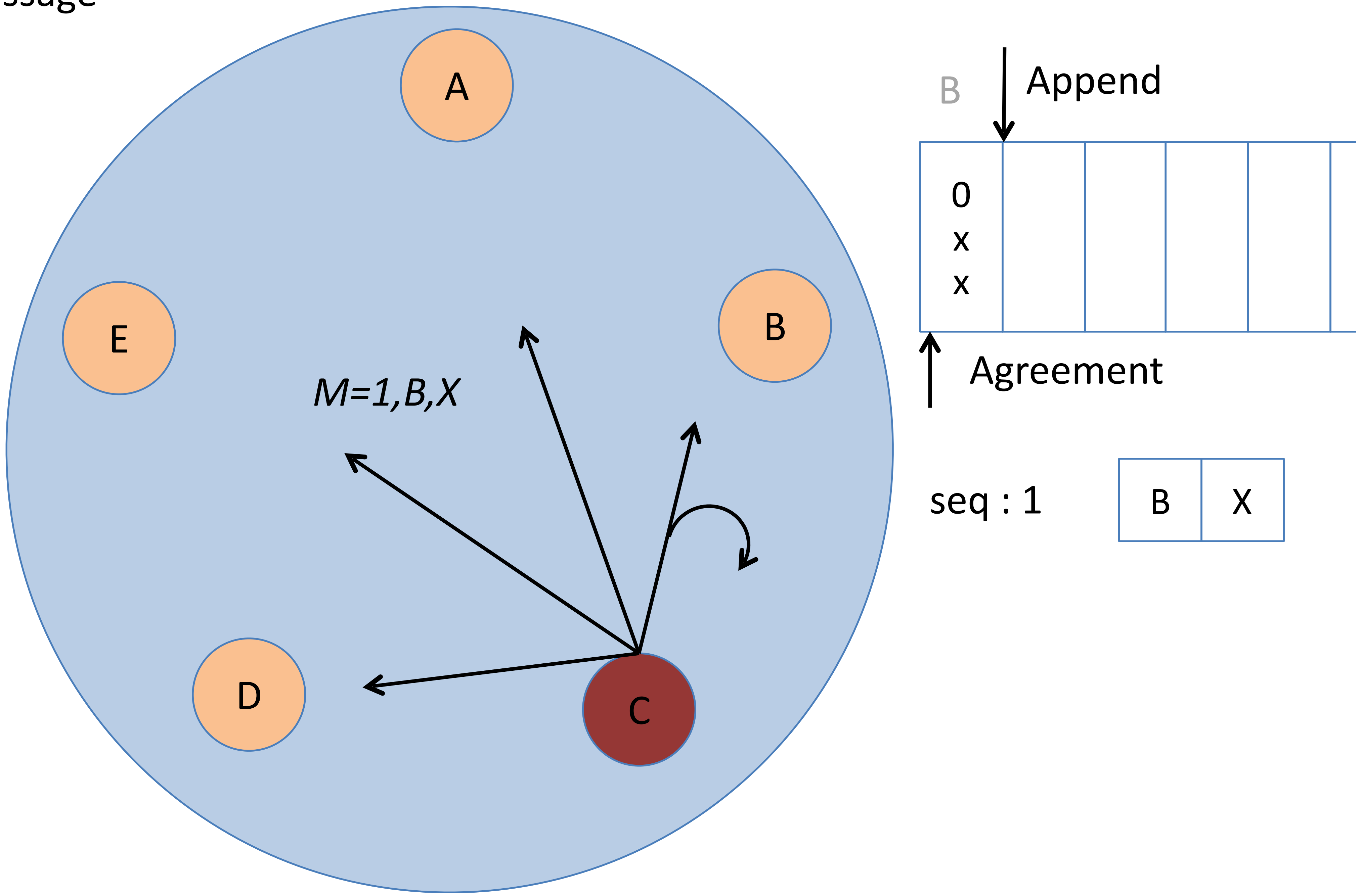
Anatomy of the Exo Protocol

Host C now has the network



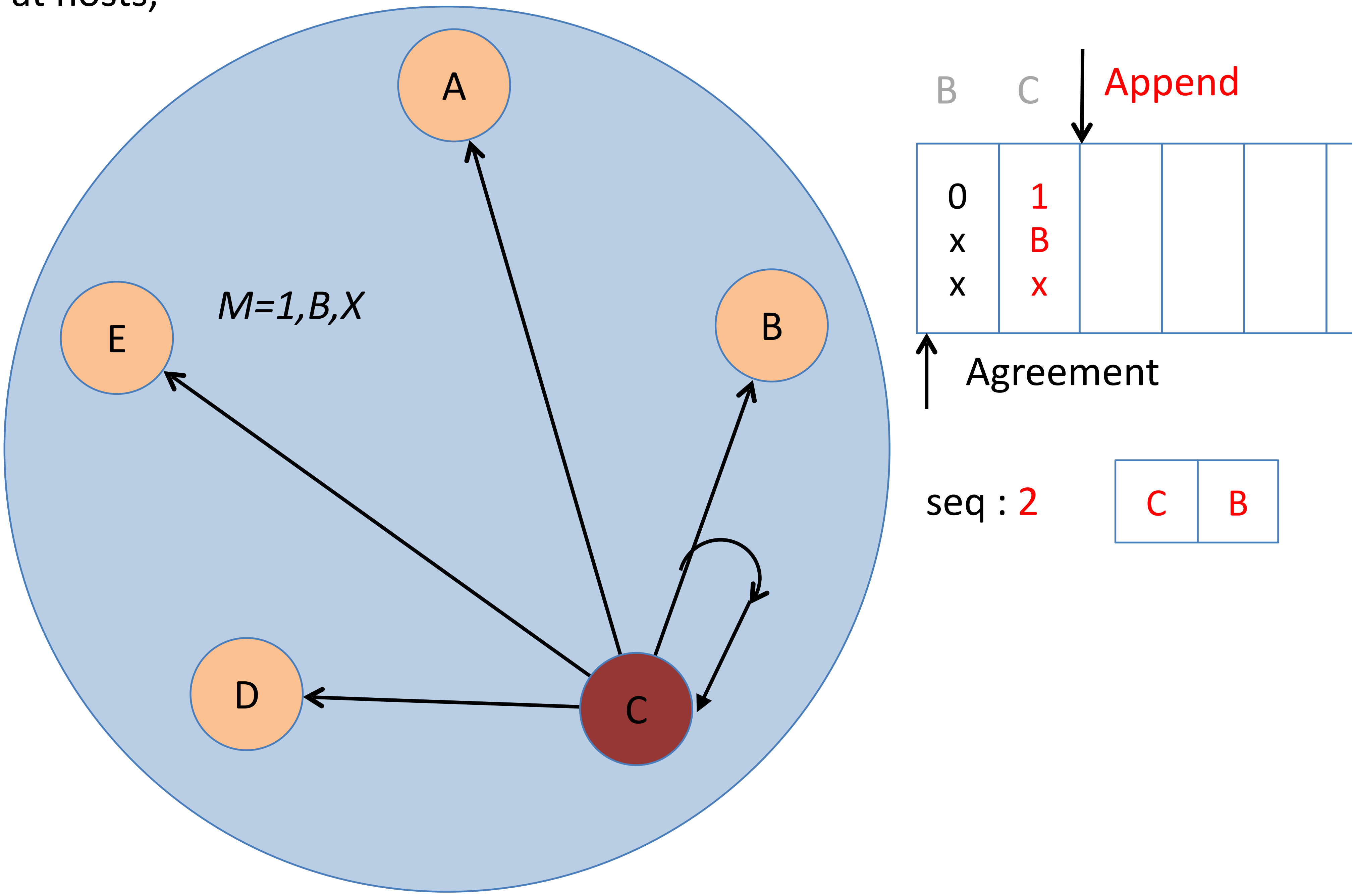
Anatomy of the Exo Protocol

Host *C* broadcasts a message



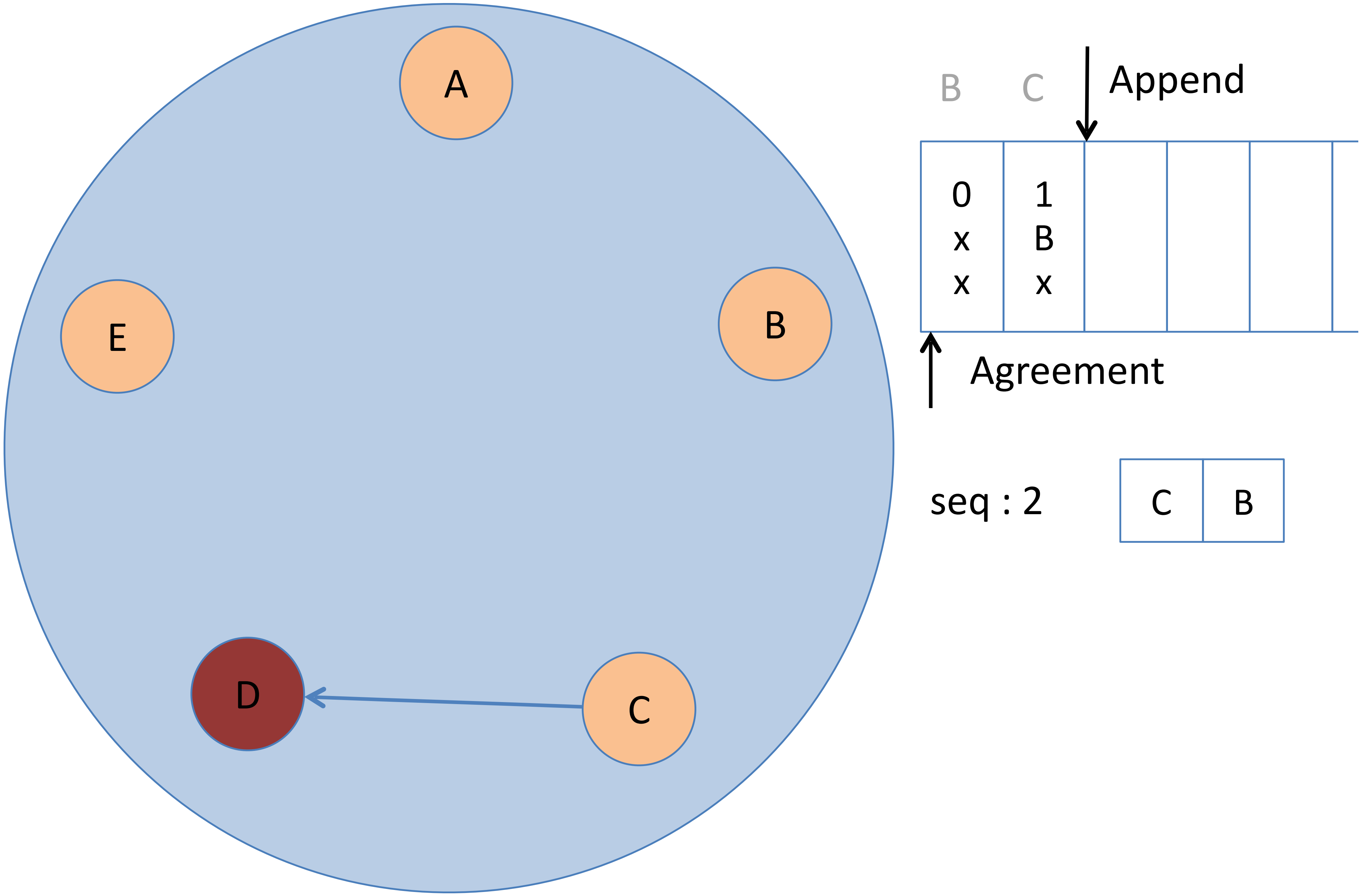
Anatomy of the Exo Protocol

Message from C arrives at hosts, causing update



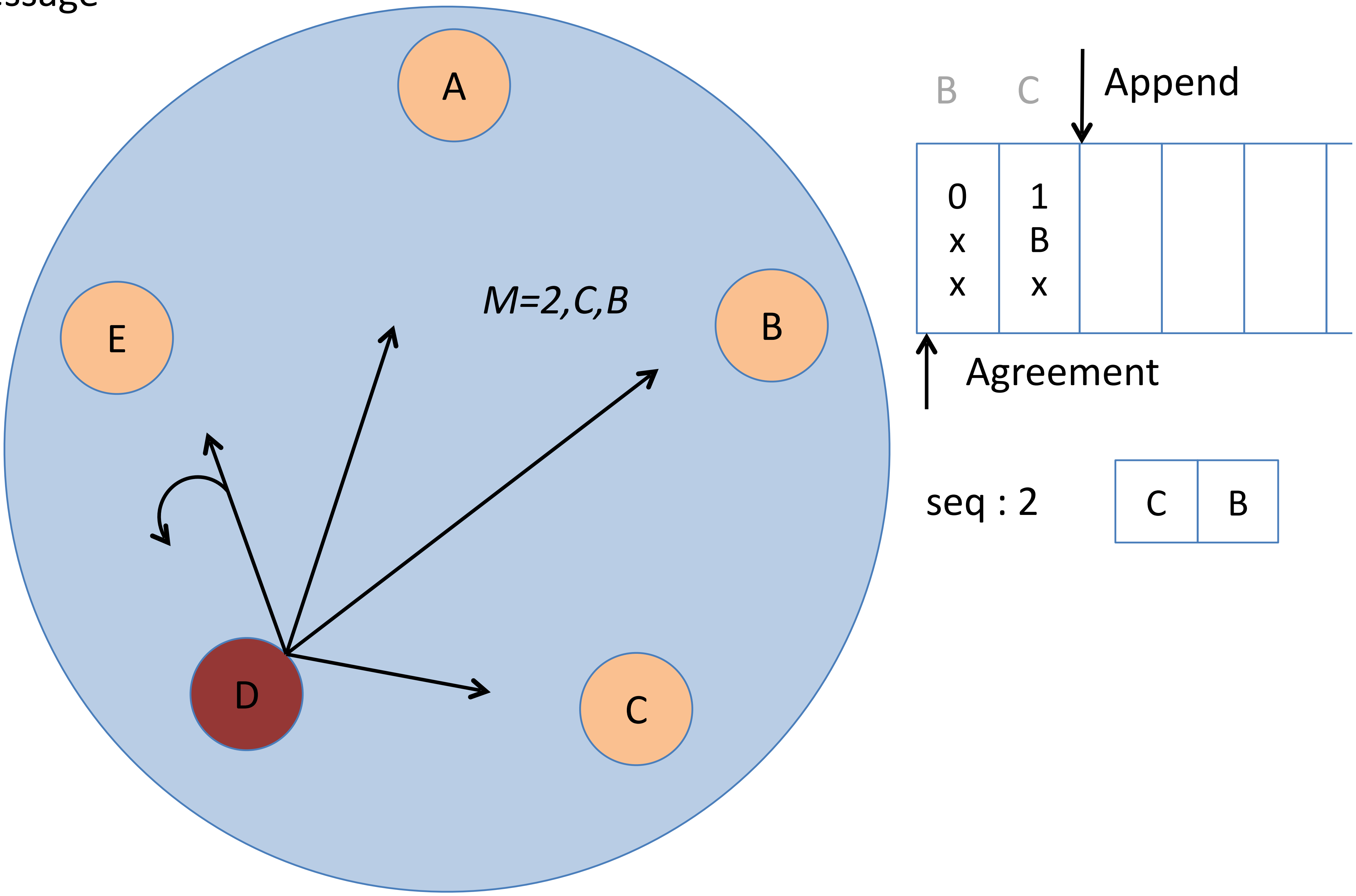
Anatomy of the Exo Protocol

D now has the token



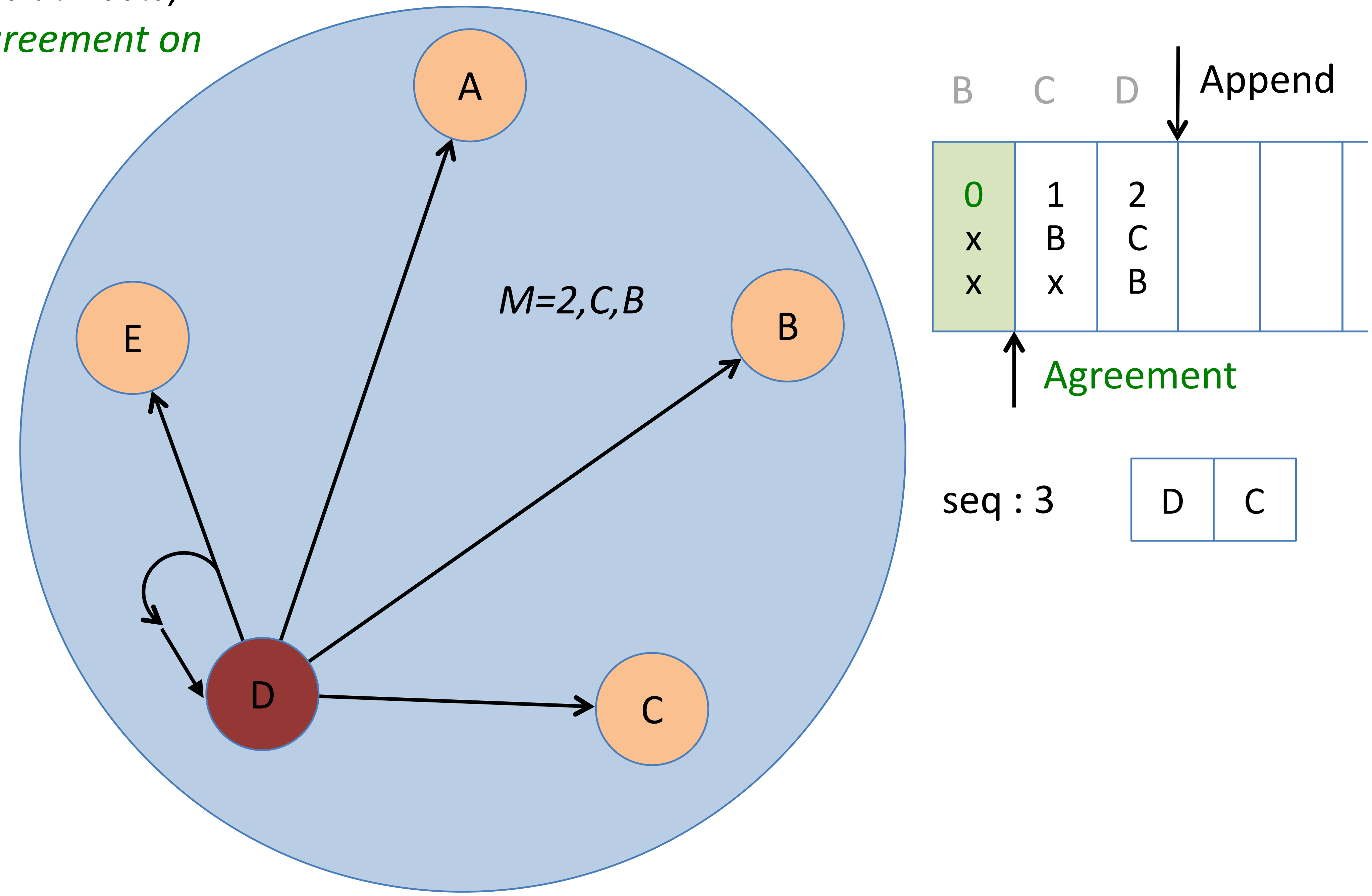
Anatomy of the Exo Protocol

Host *D* broadcasts a message



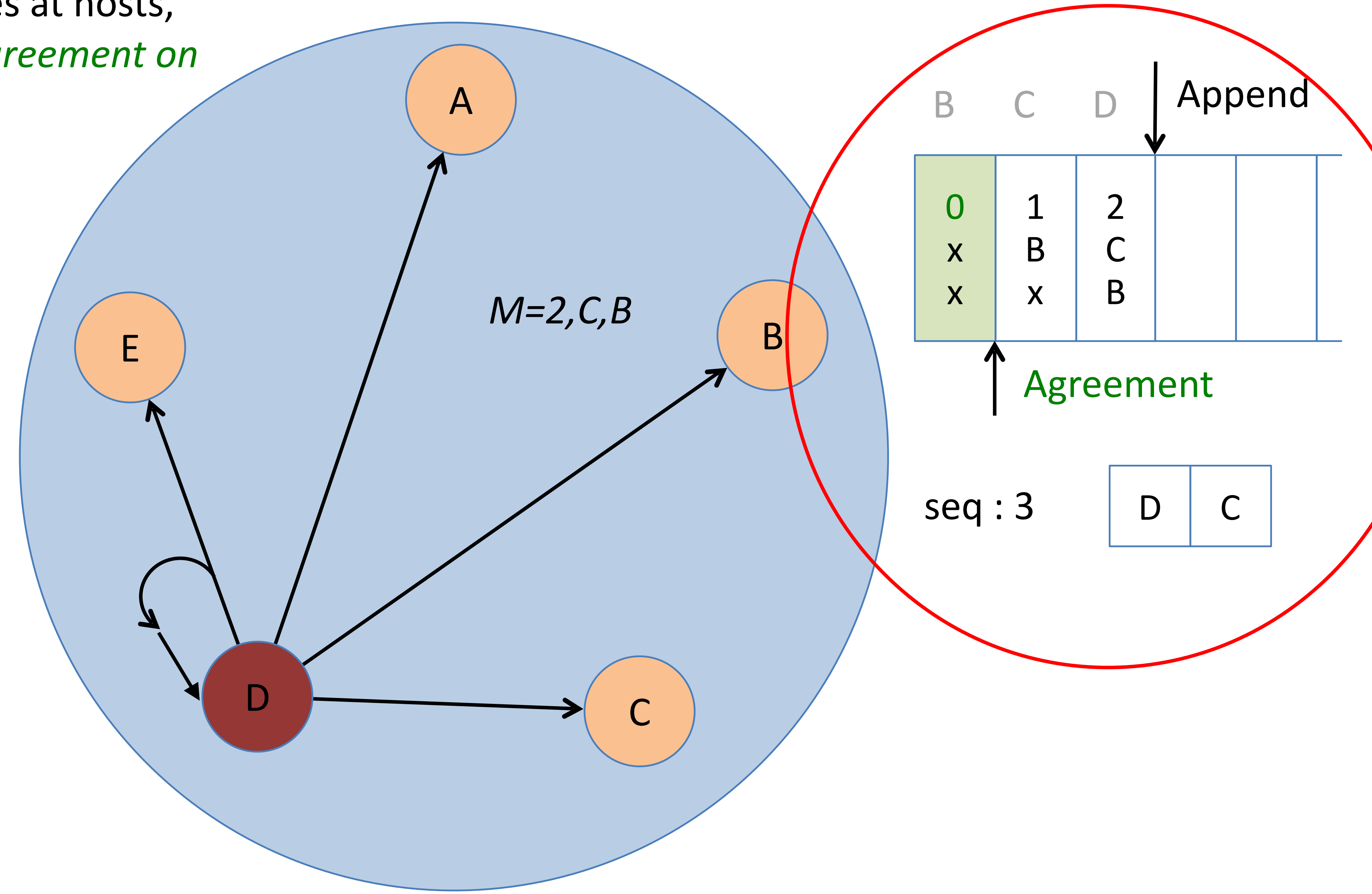
Anatomy of the Exo Protocol

Message from D arrives at hosts, causing *update and agreement on sequence number 0*

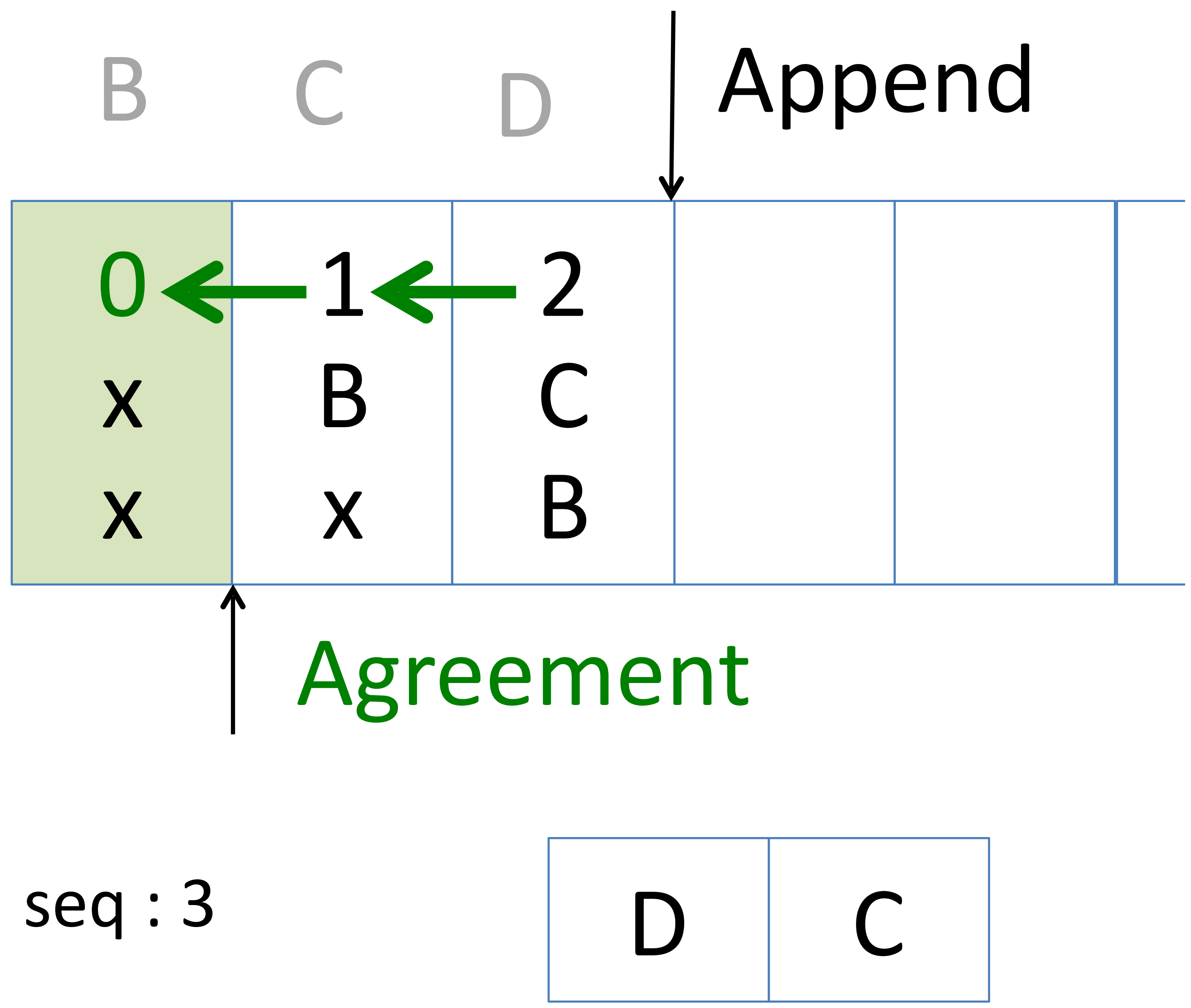


Zooming in…

Message from D arrives at hosts, causing *update and* *agreement on sequence number 0*



Zooming in…



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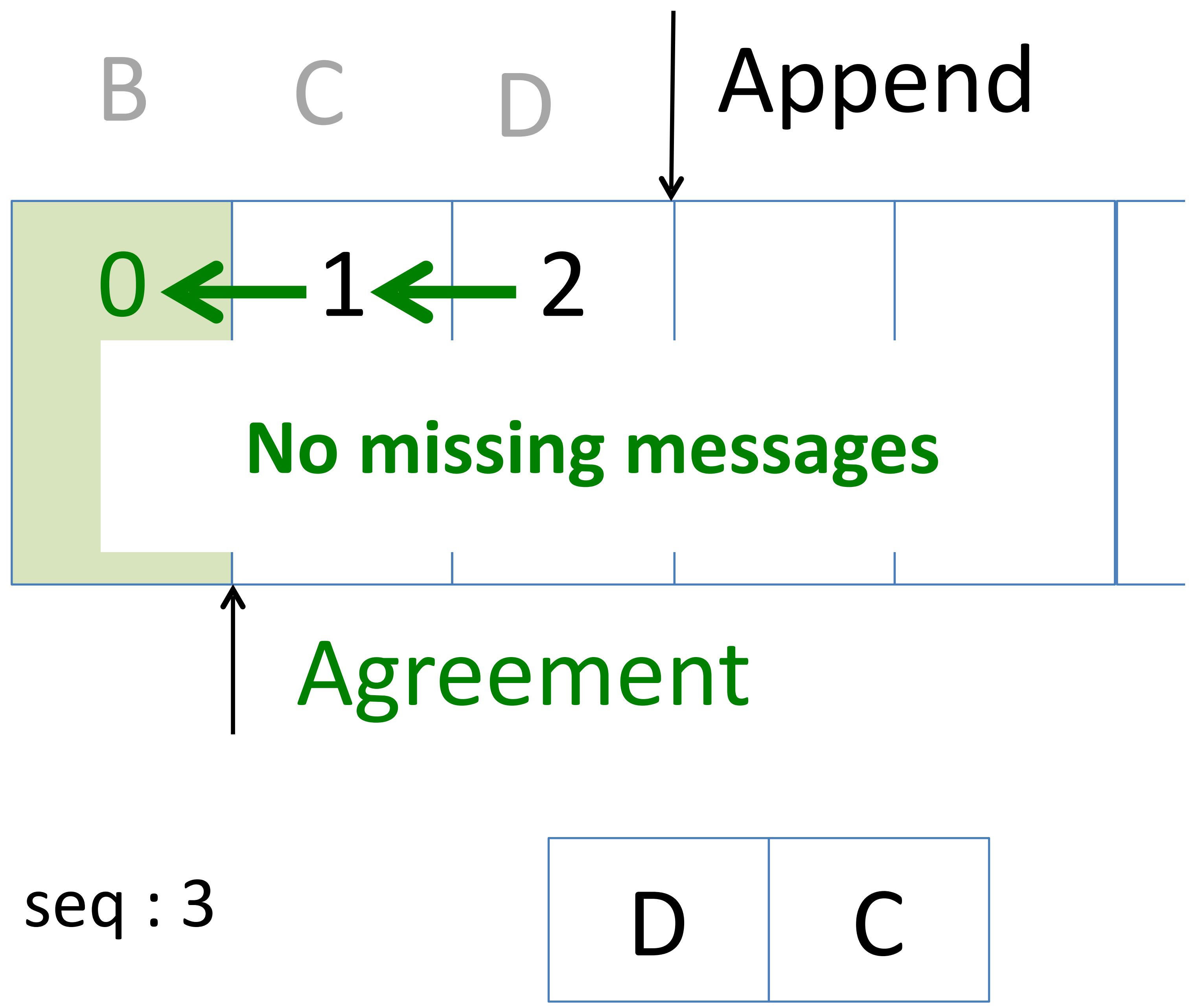
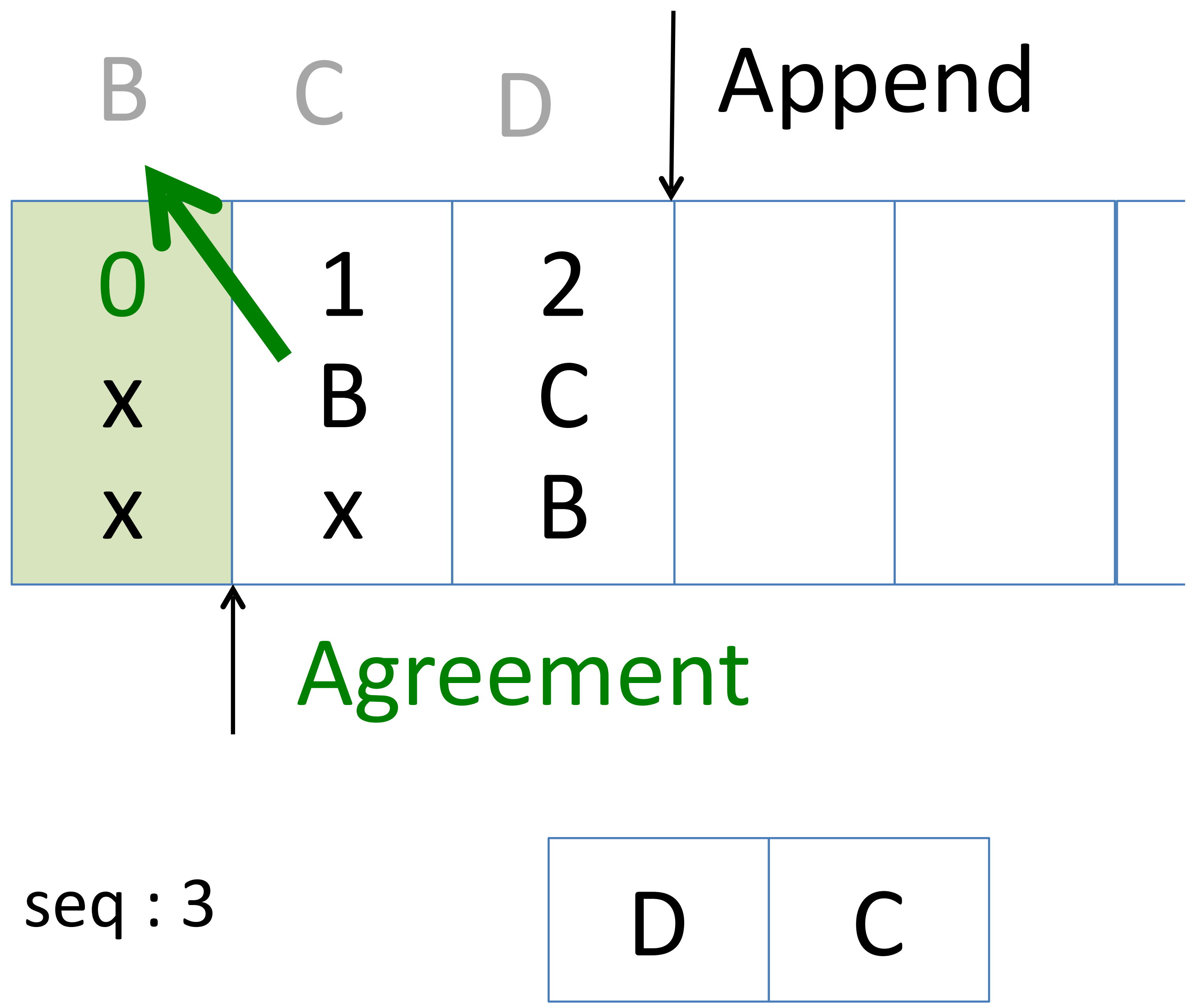


NB: Using a 64bit sequence number gives >400 years operation at 1 message per nano-second.

Zooming in…



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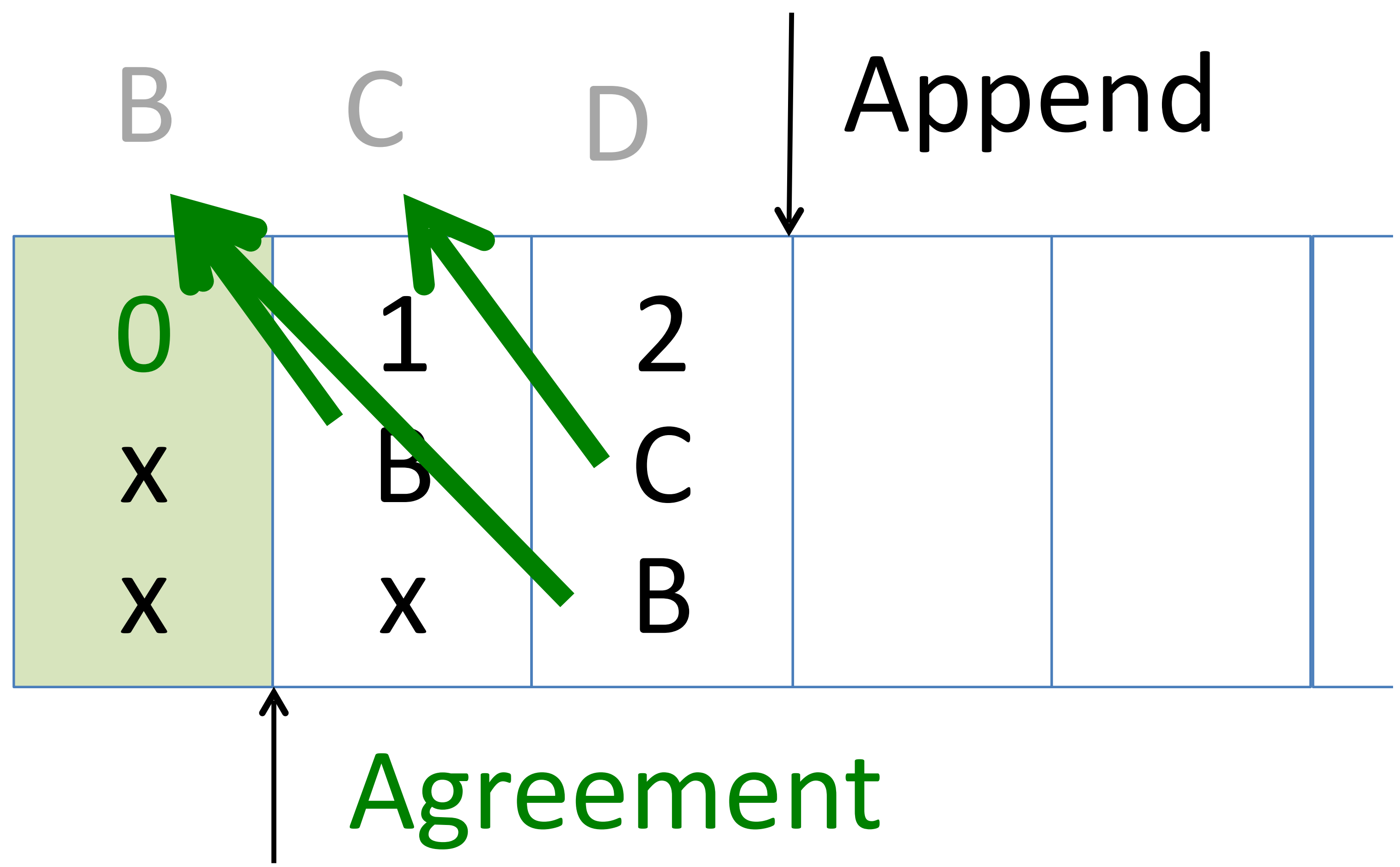
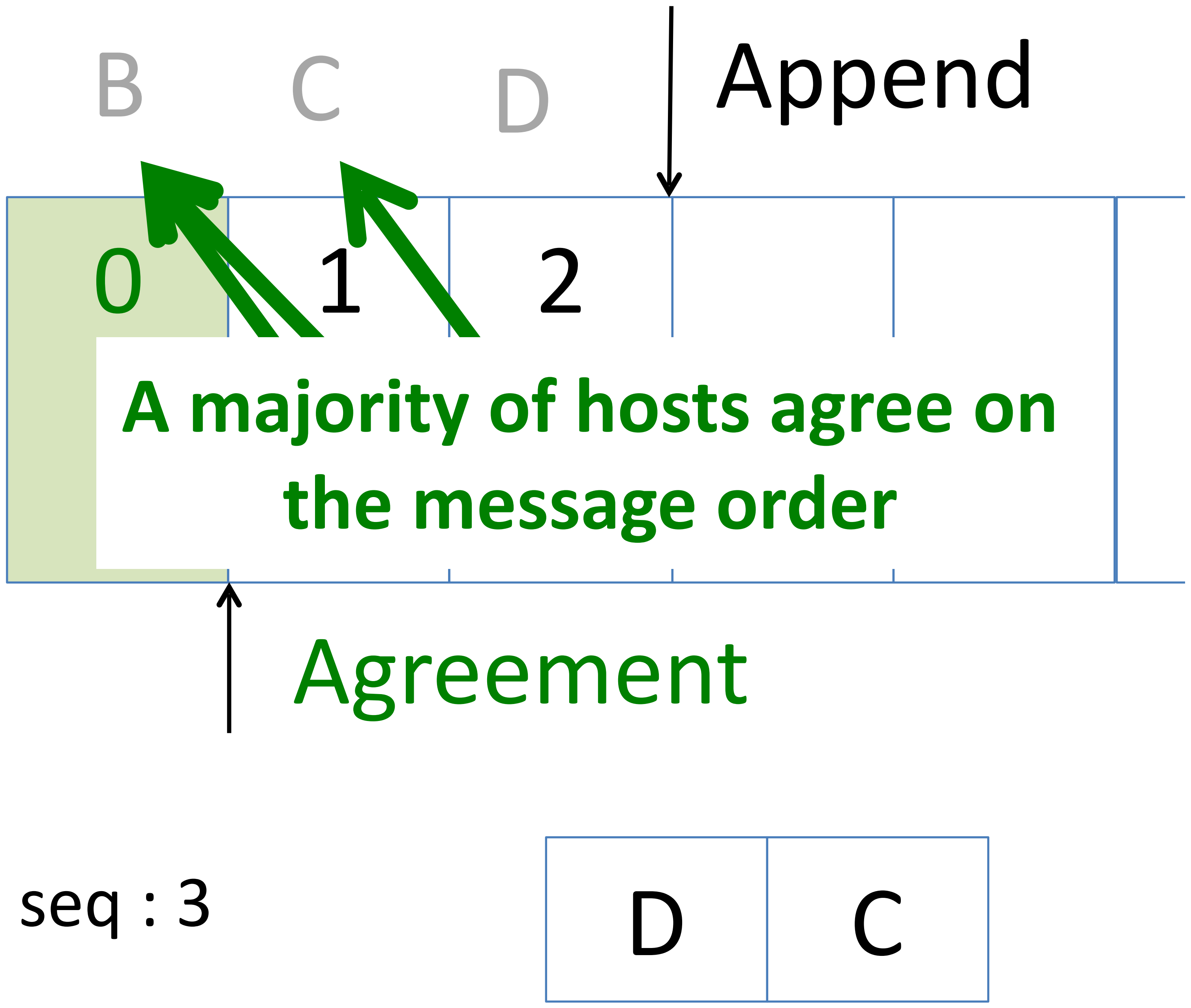


seq : 3

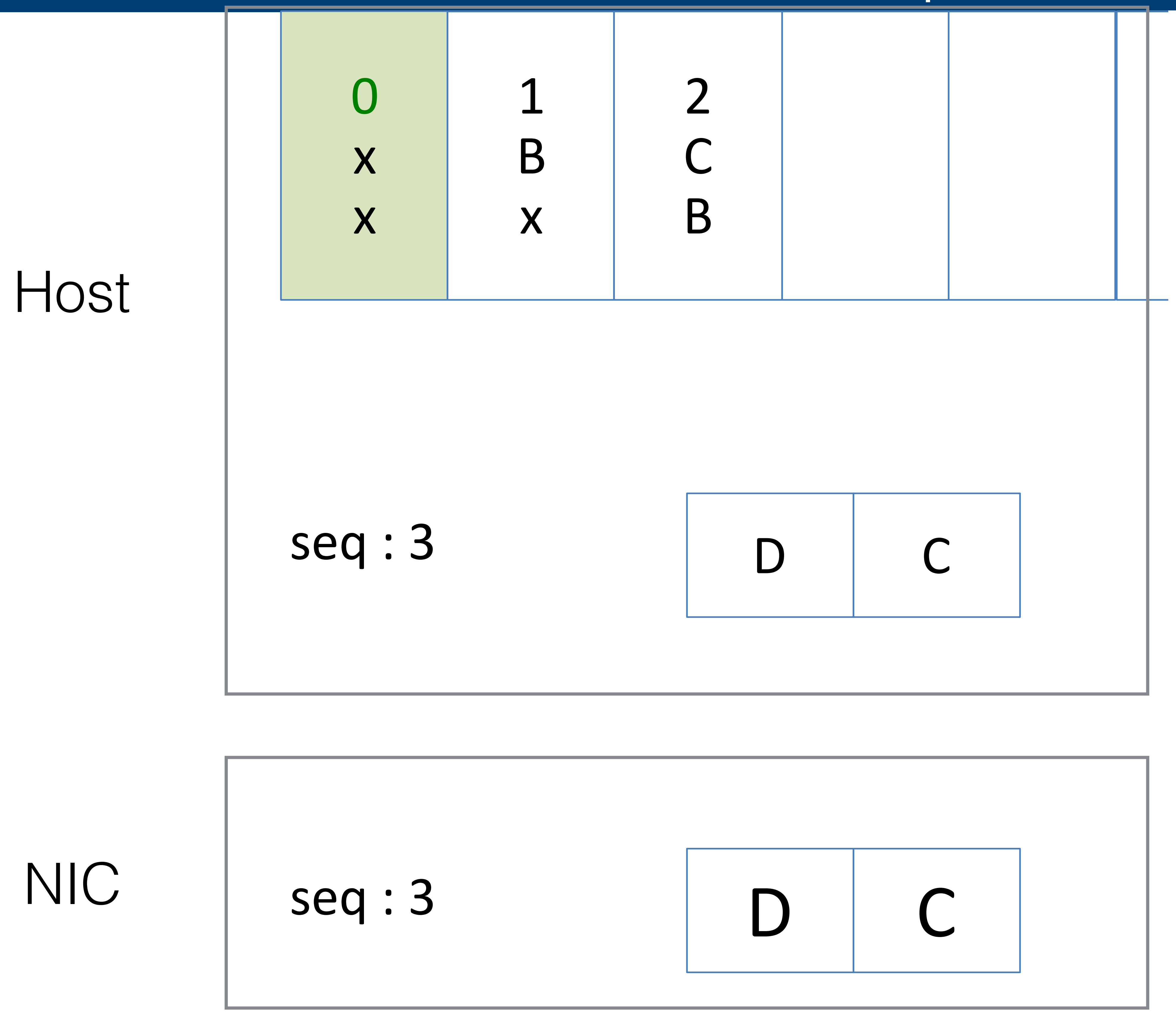
D	C

Zooming in…



NB: Assuming at most 256 nodes, message history is 128B and can

How to accelerate the protocol?



Implementation

- Protocol implemented over CamIO
  - Runs on TCP, Broadcast UDP, Raw Frames and OpenOnload (ExaSock)
- Offload engine (mostly) implemented in FPGA
  - Currently working for empty messages.

Results

Linux TCP	36µs/msg	28K msg/sec)
Linux UDP	29µs/msg	(34K msg/sec)
Linux UDP (broadcast)	16µs/msg	(62K msg/sec)
Linux TCP (loopback)	9µs/msg	(110K msg/sec)
Linux UDP (loopback)	4us/msg	(231K msg/sec)
Libexanic (raw frames)	3µs/msg	(359K msg/sec)
Exo HW offload	0.4µs/msg	(2500K msg/sec)

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Exo HW offload	**0.4μs/msg**	**(2500K msg/sec)**

≈ 100x Faster

Concuslisions

- Exo is a work in progress
- We use a specialised network and hardware offload to build fast scalable coordination for rack-scale architectures
- Initial results suggest at least a 100x speed improvement over existing protocols/systems

Questions?

Thanks to our sponsors

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EXABLAZE

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Engineering and Physical Sciences Research Council

Research

Systems

Group

srg@cambridge:~$

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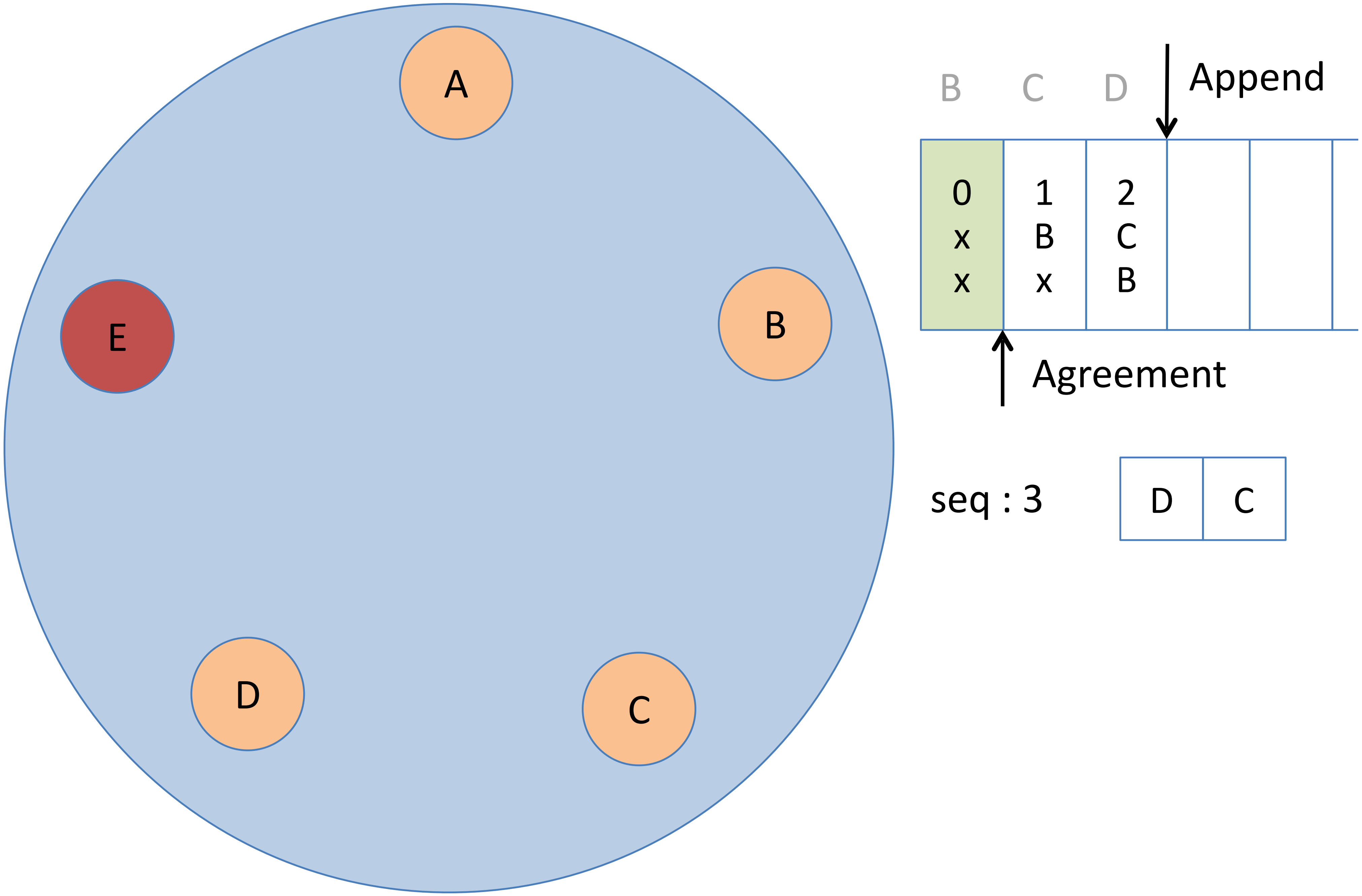
Backups

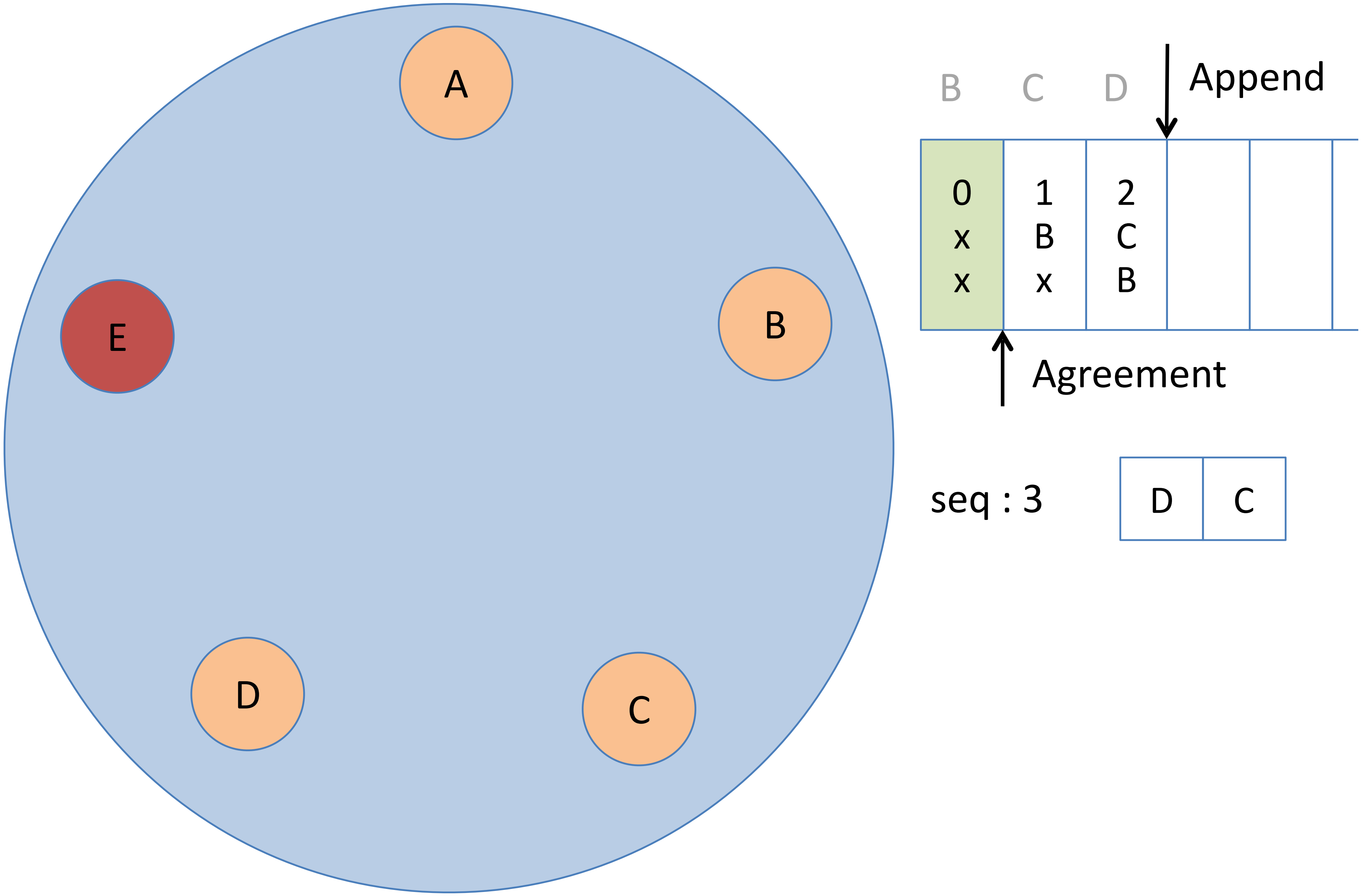
Anatomy of the Exo Protocol

E now has the token



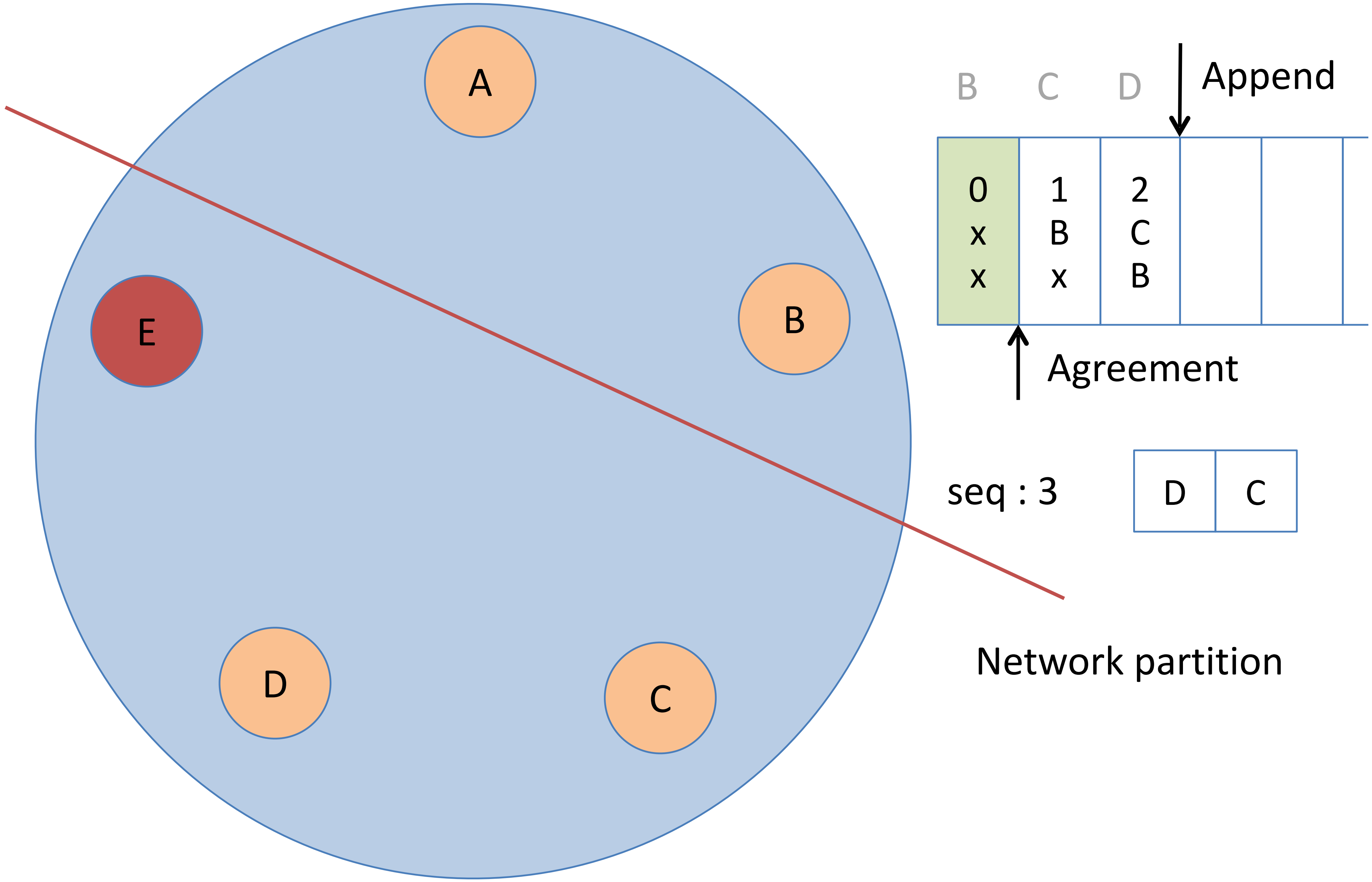
Handling Errors?

E now has the token



Handling Errors?

Consider the following pathological case



Handling Errors?

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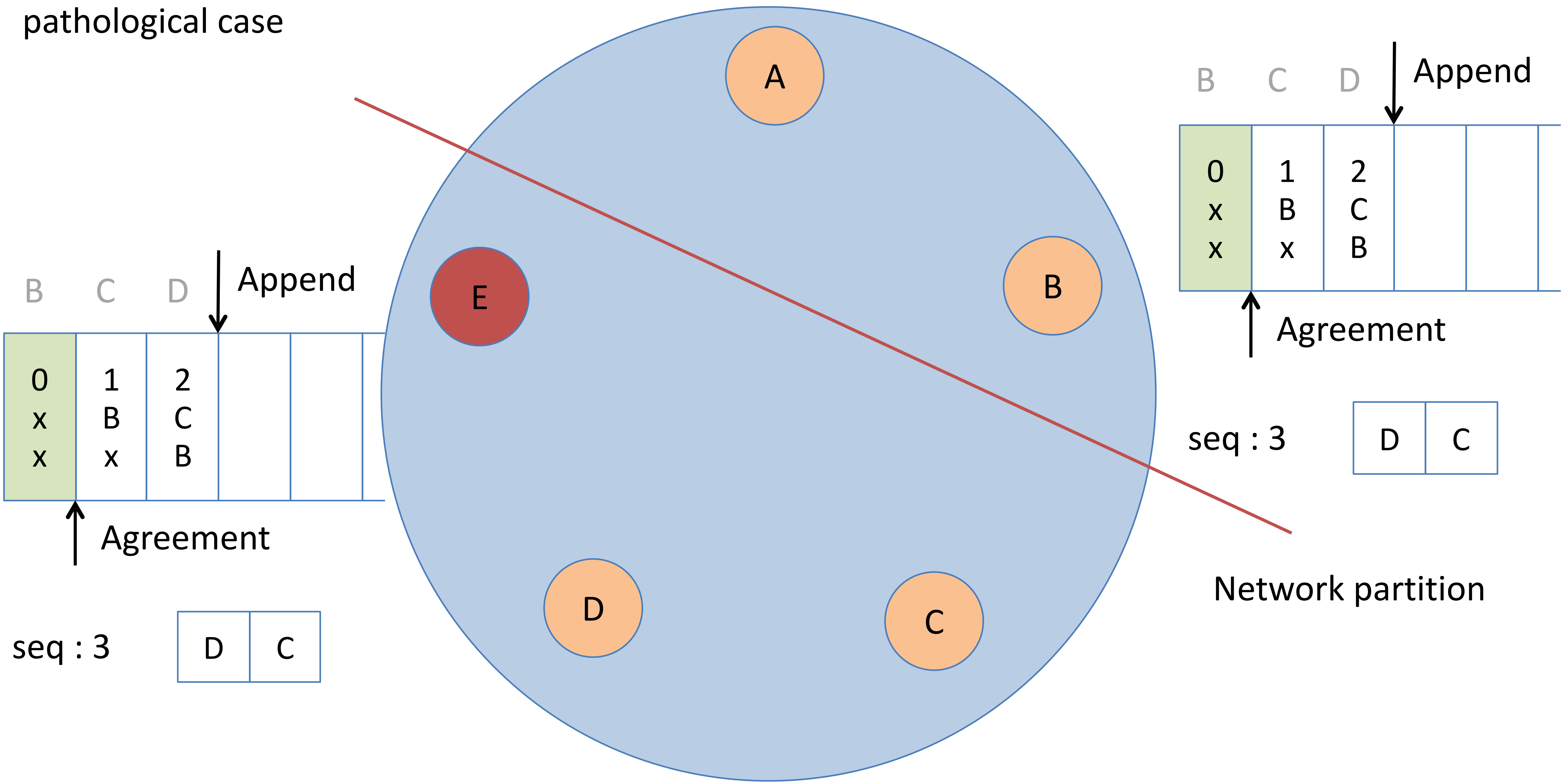
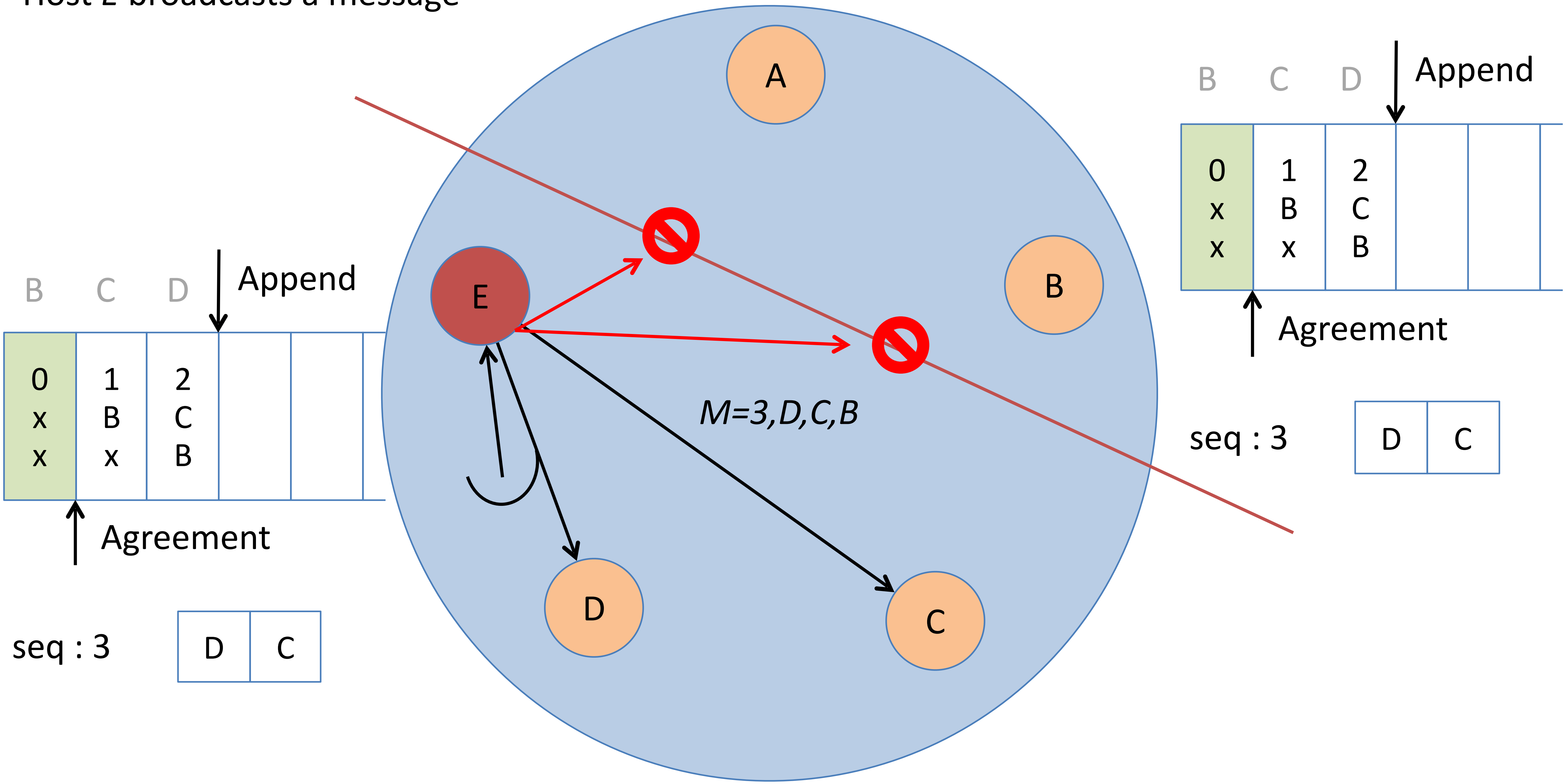


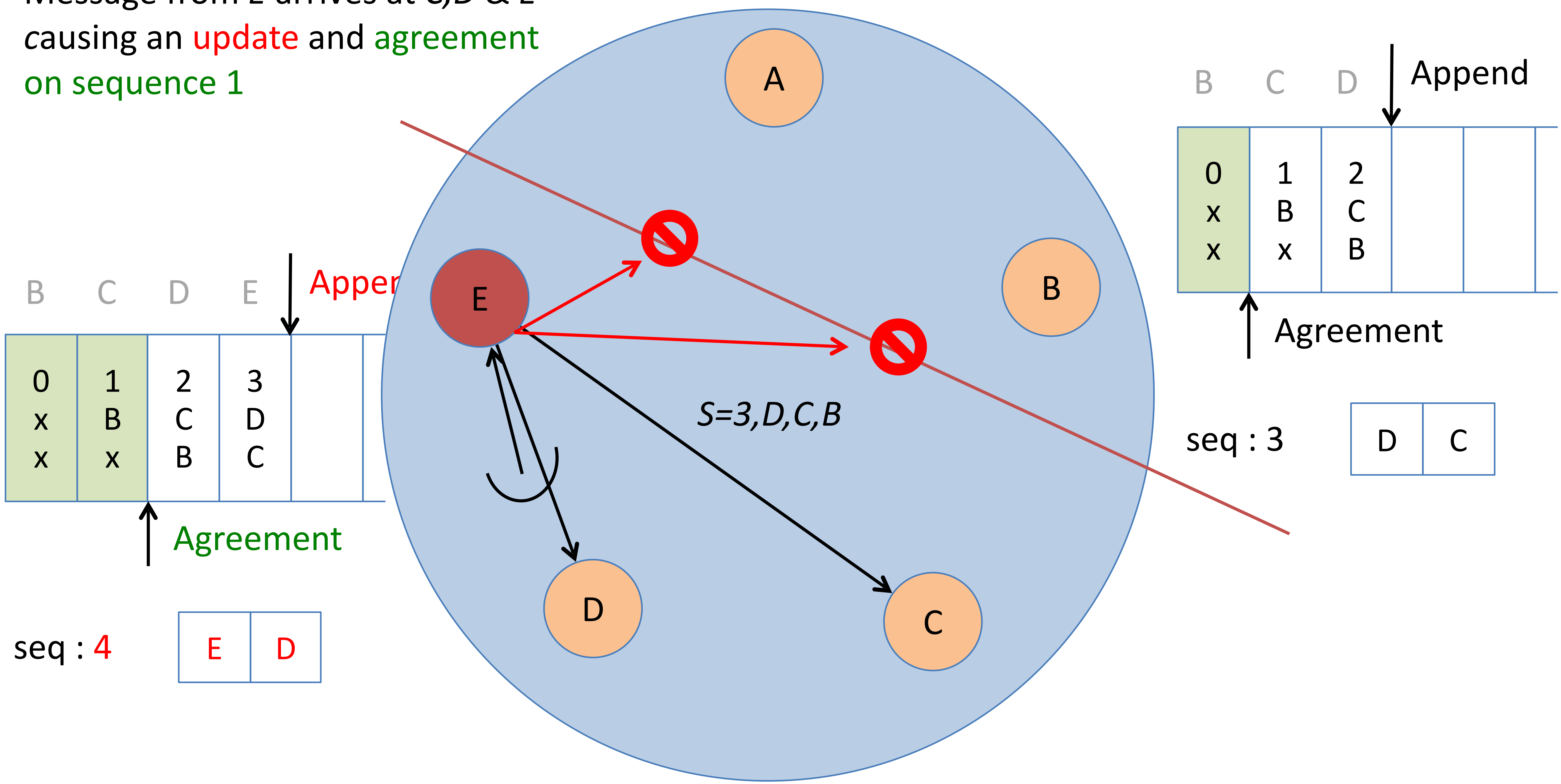
Handling Errors?

Host *E* broadcasts a message



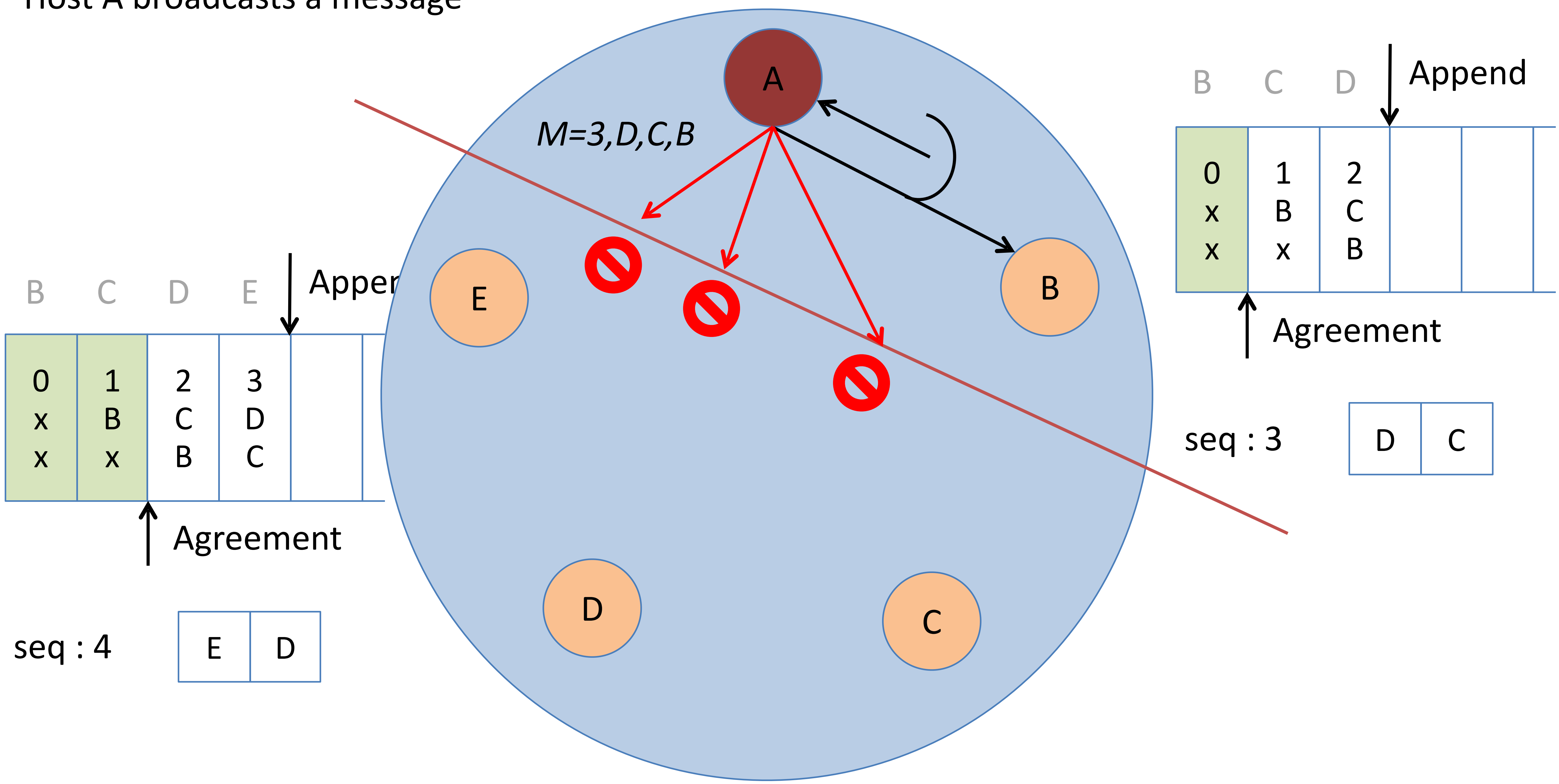
Handling Errors?

Message from *E* arrives at *C,D* & *E* causing an update and agreement on sequence 1



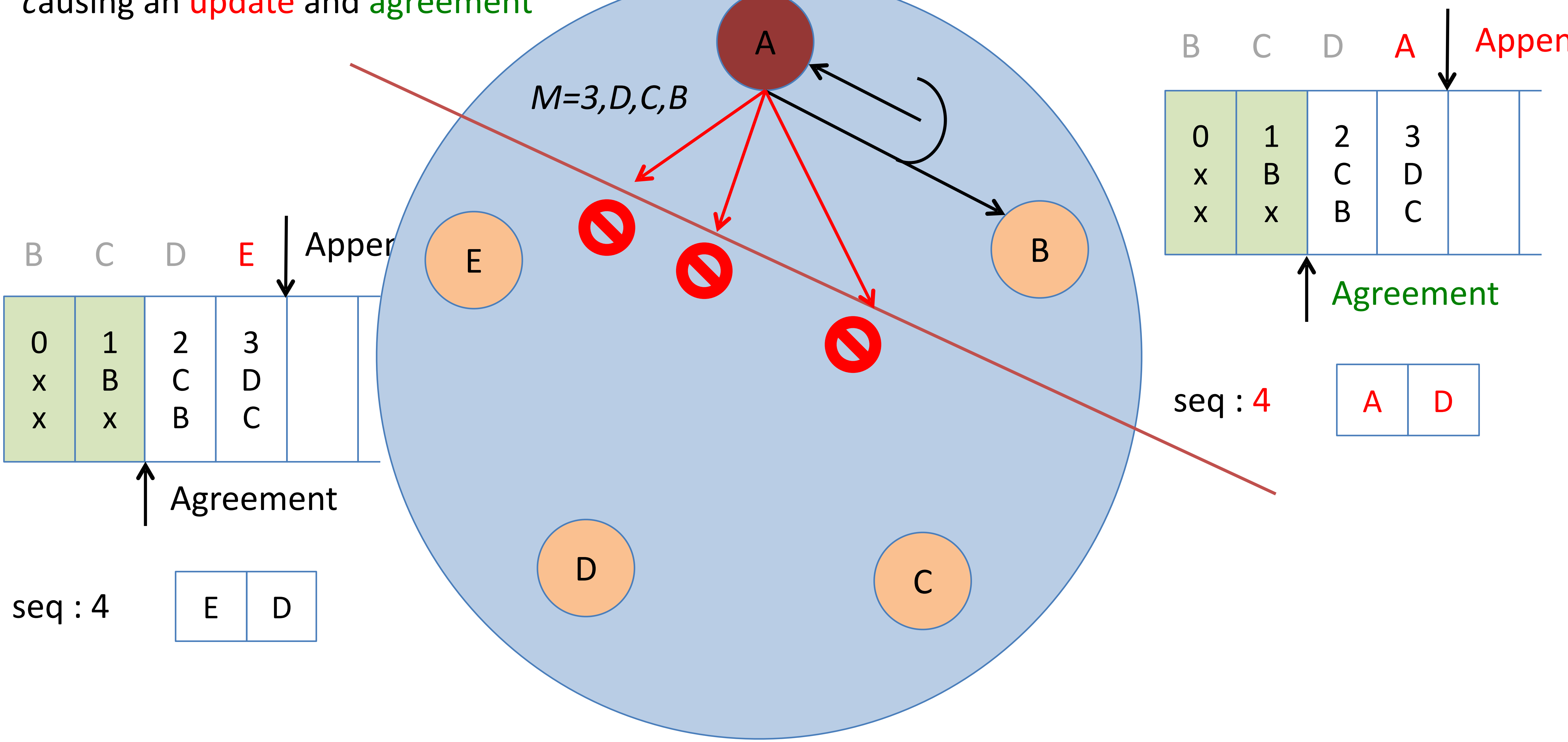
Handling Errors?

Host A broadcasts a message



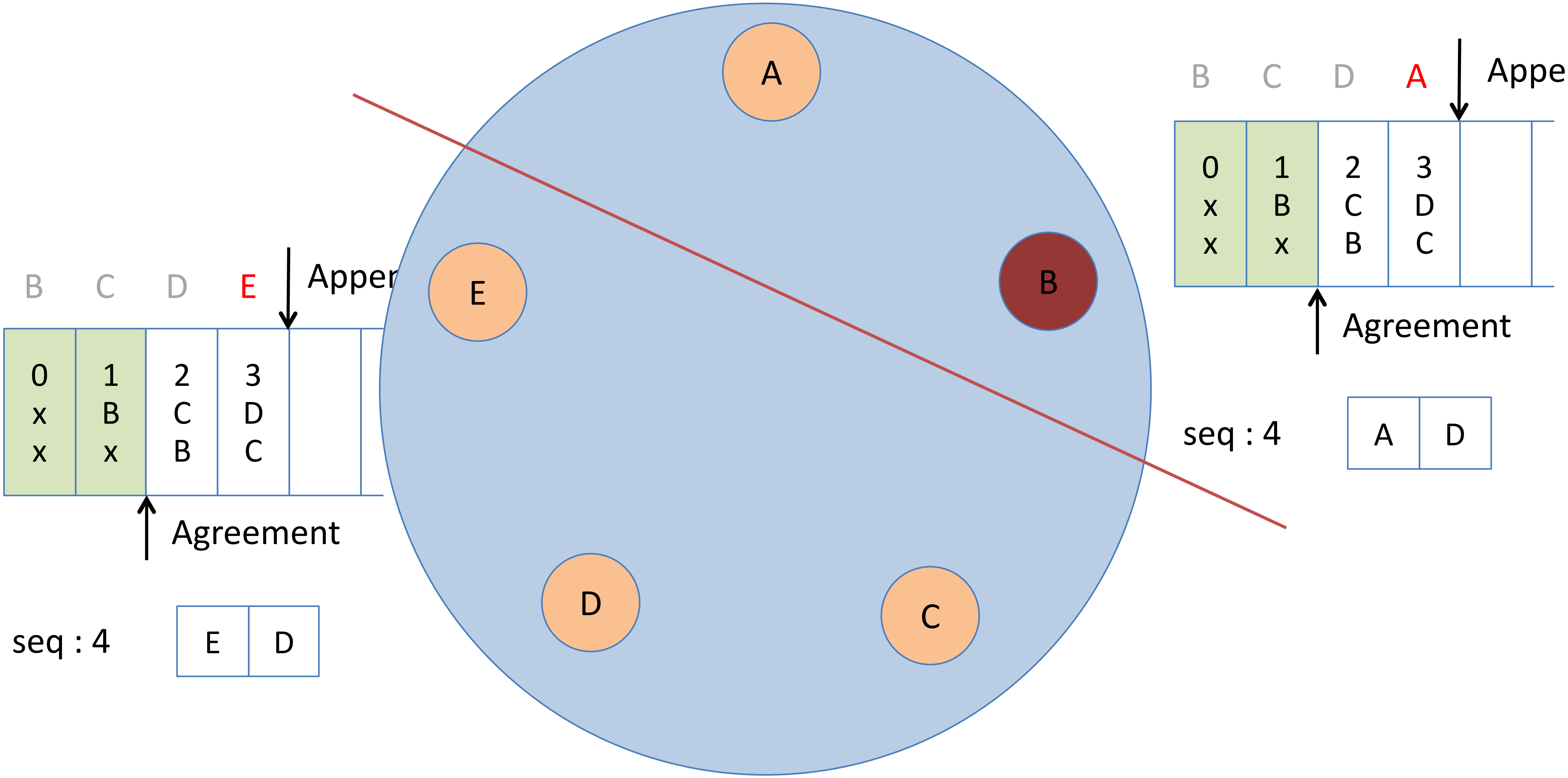
Handling Errors?

Message from A arrives at A & B, causing an update and agreement



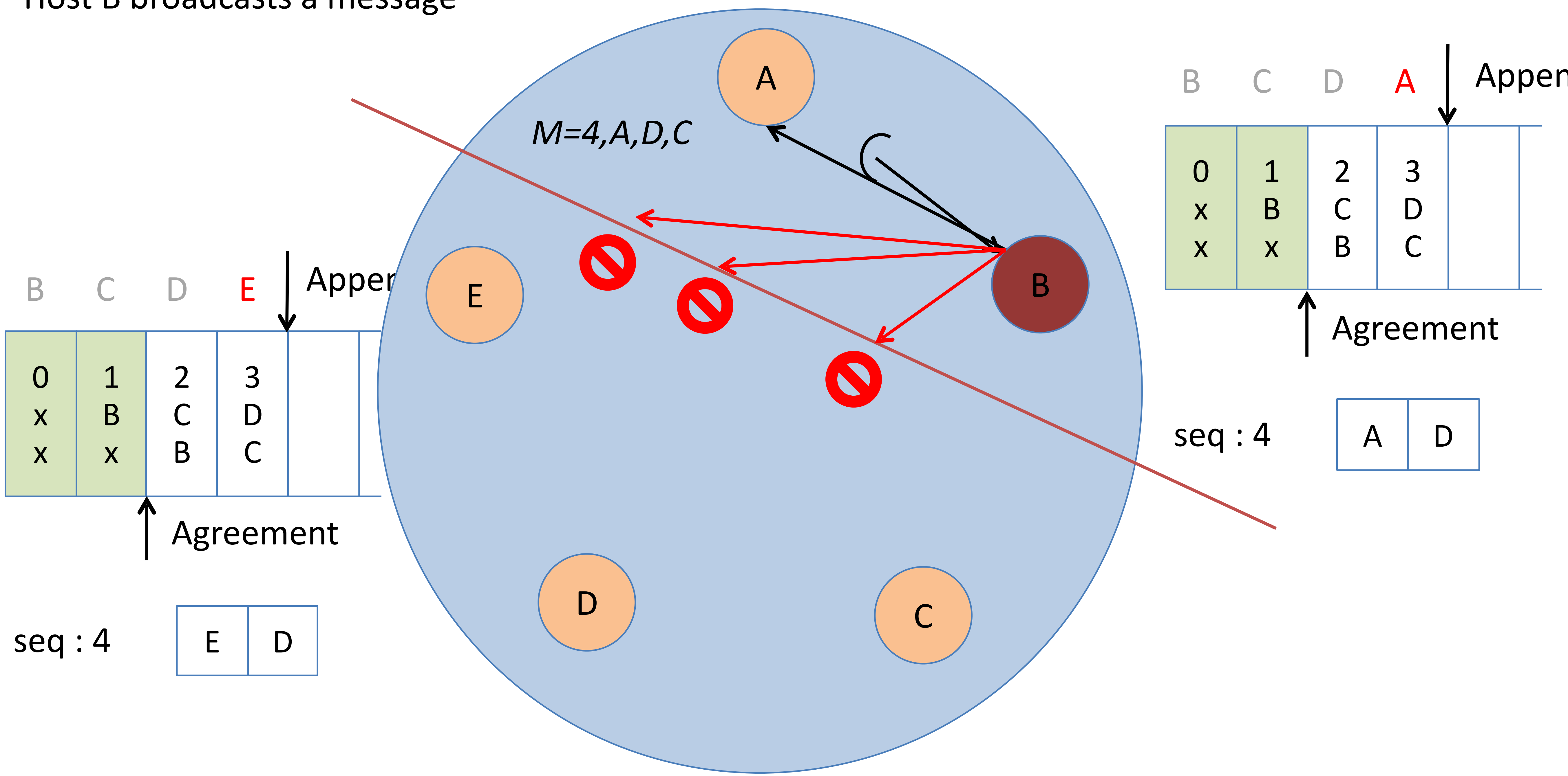
Handling Errors?

B now has the token



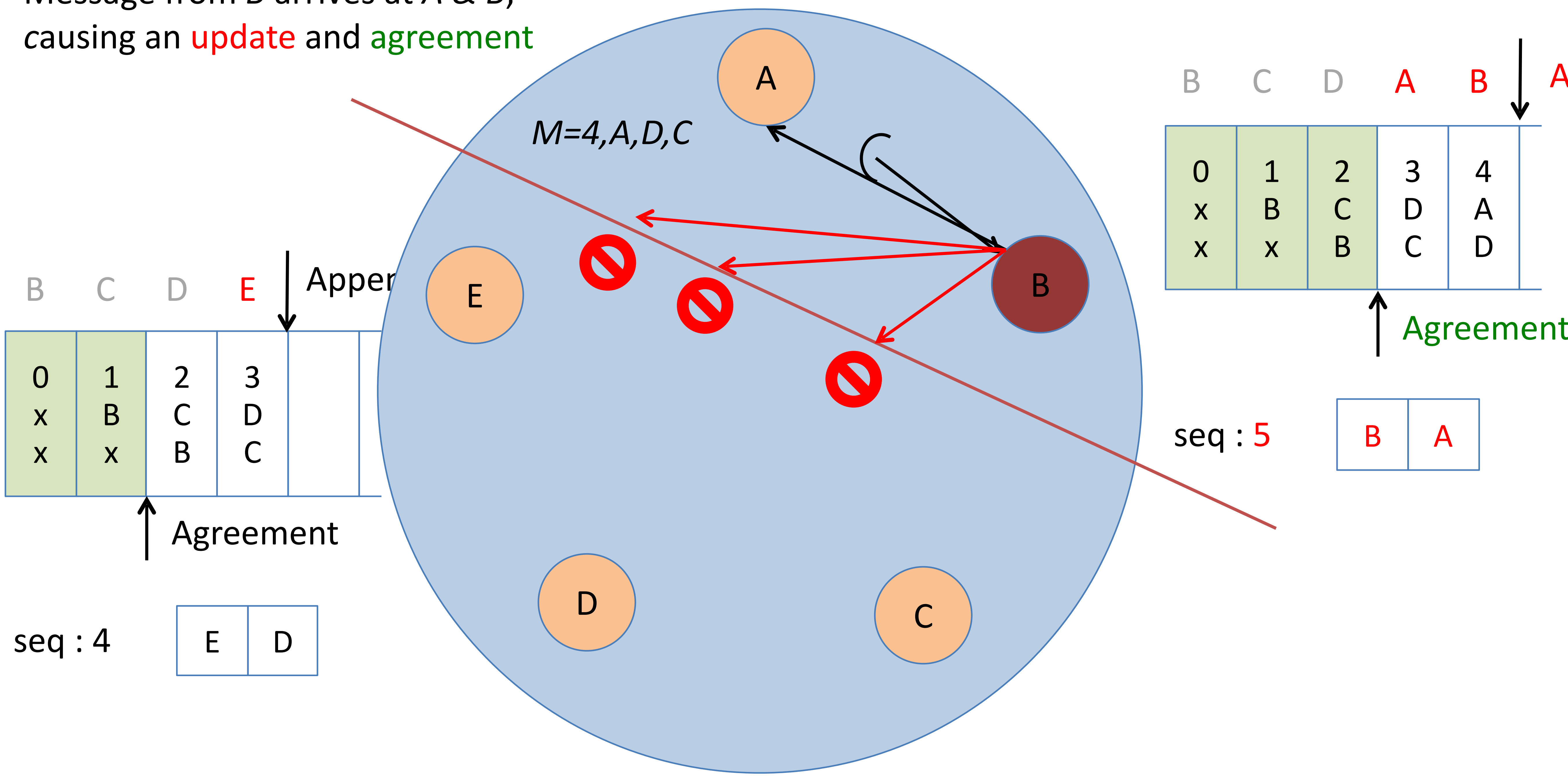
Handling Errors?

Host B broadcasts a message



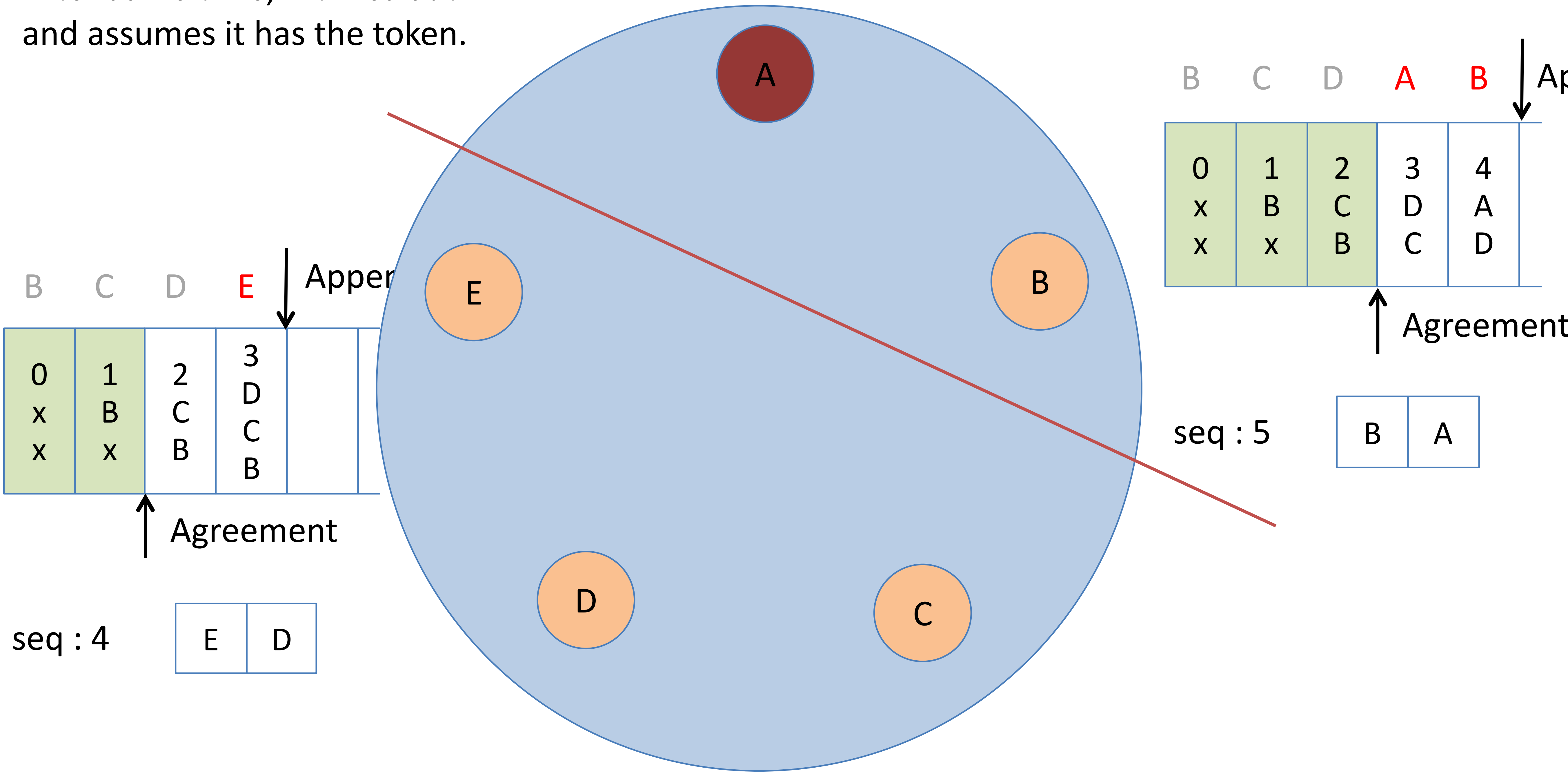
Handling Errors?

Message from *B* arrives at *A & B*, causing an update and agreement



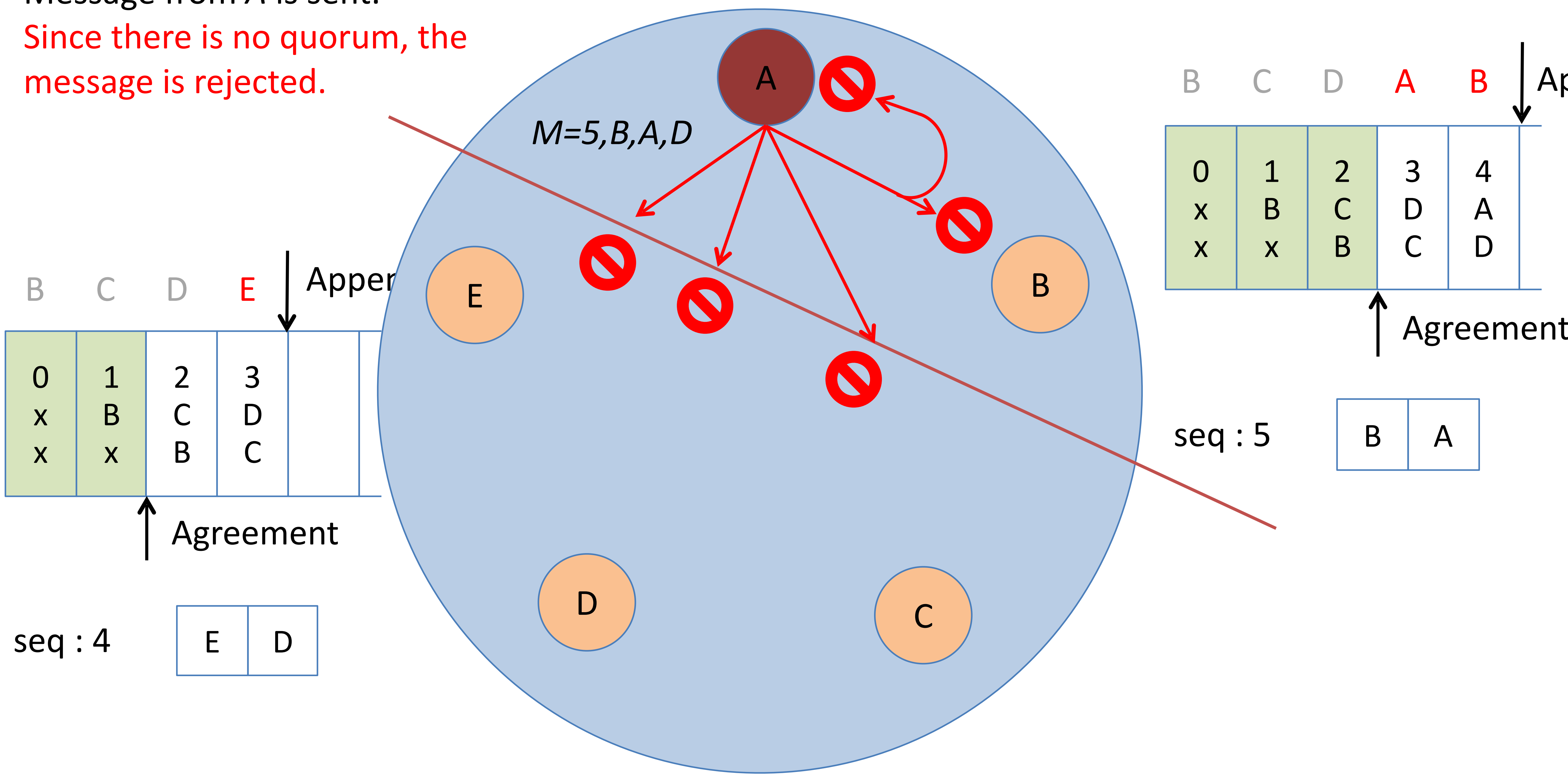
Handling Errors?

After some time, *A* times out and assumes it has the token.



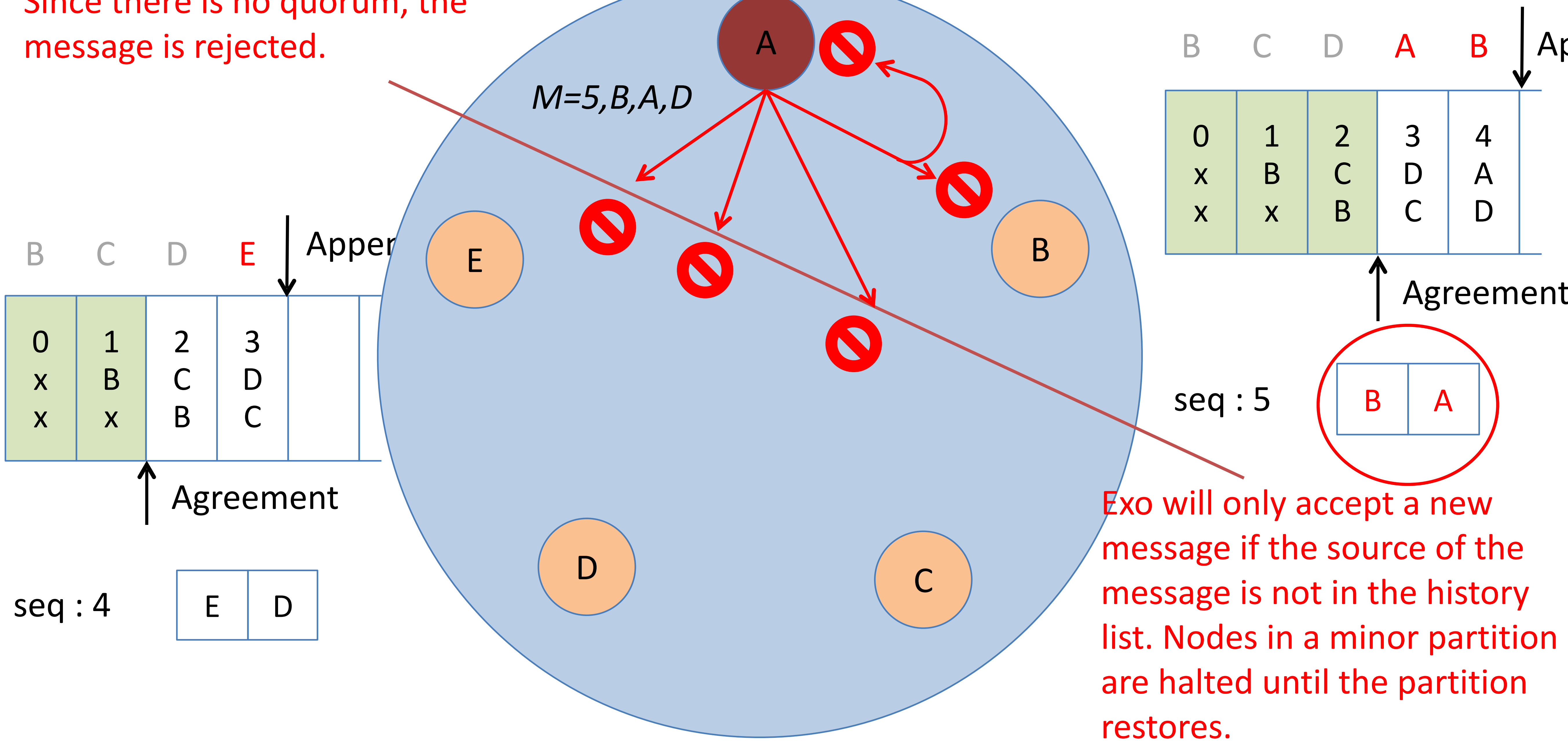
Handling Errors?

Message from *A* is sent.
Since there is no quorum, the message is rejected.



Handling Errors?

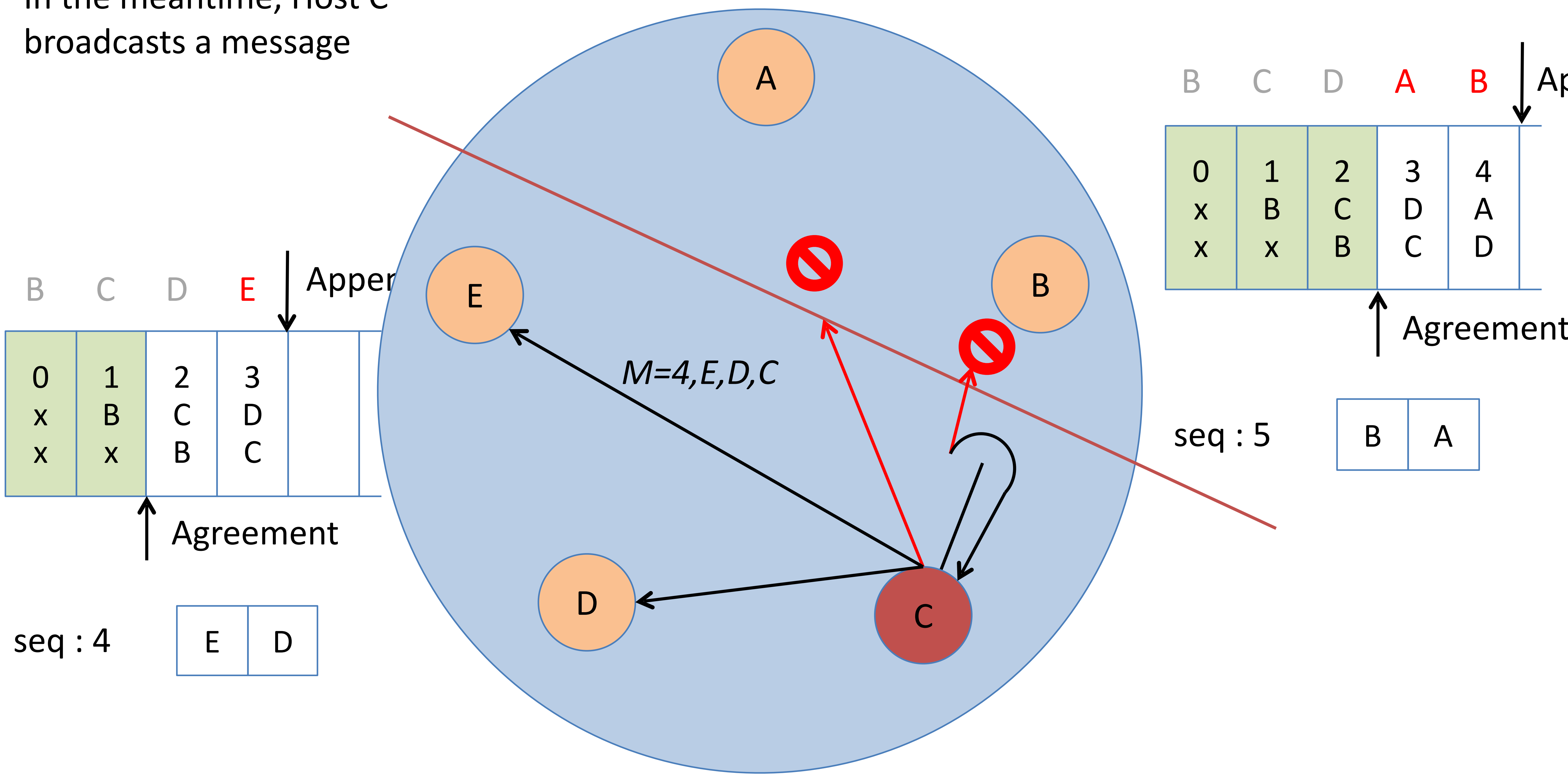
Message from *A* is sent.
Since there is no quorum, the message is rejected.



Exo will only accept a new message if the source of the message is not in the history list. Nodes in a minor partition are halted until the partition restores.

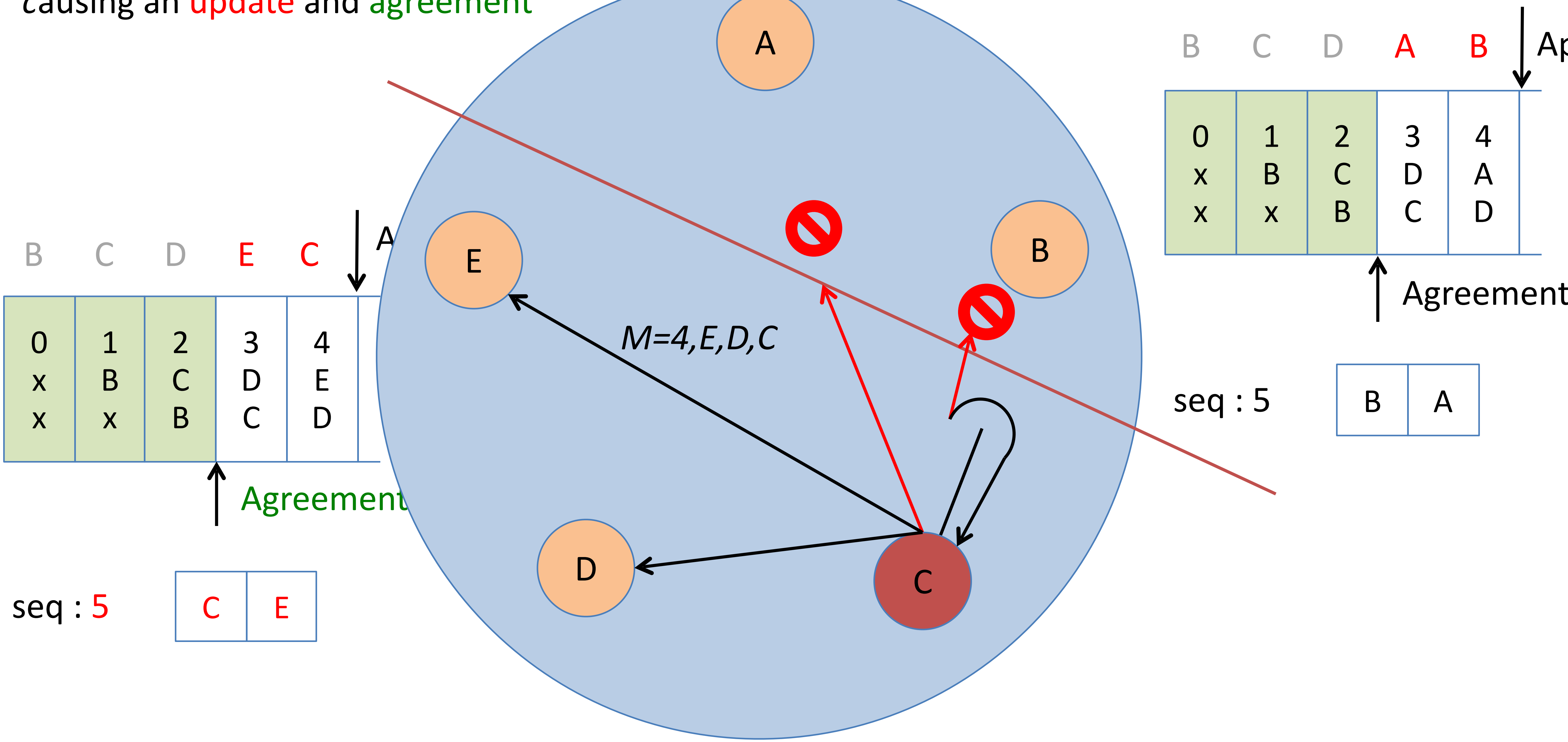
Handling Errors?

In the meantime, Host C broadcasts a message



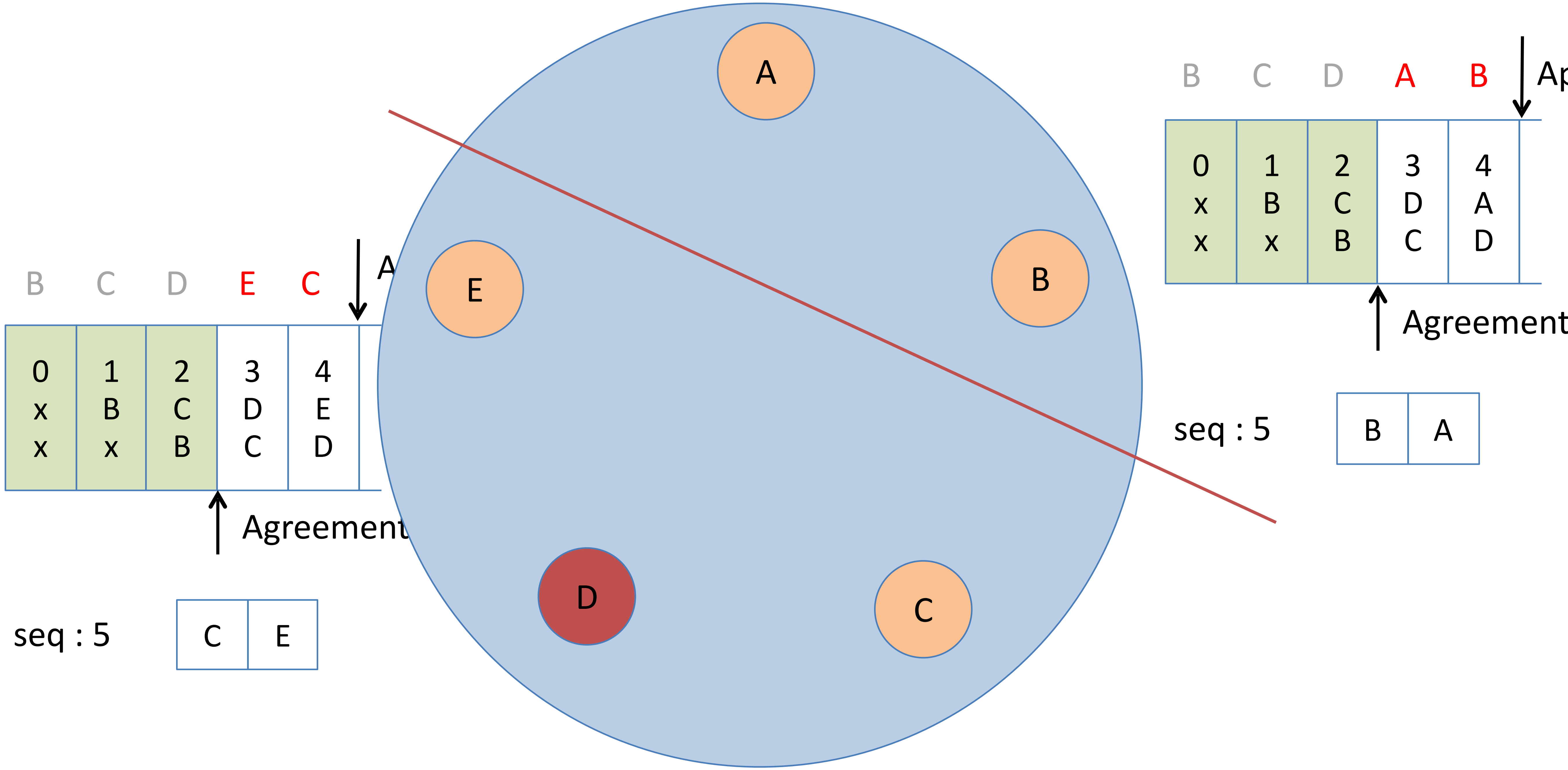
Handling Errors?

Message from *B* arrives at *A & B*, causing an update and agreement



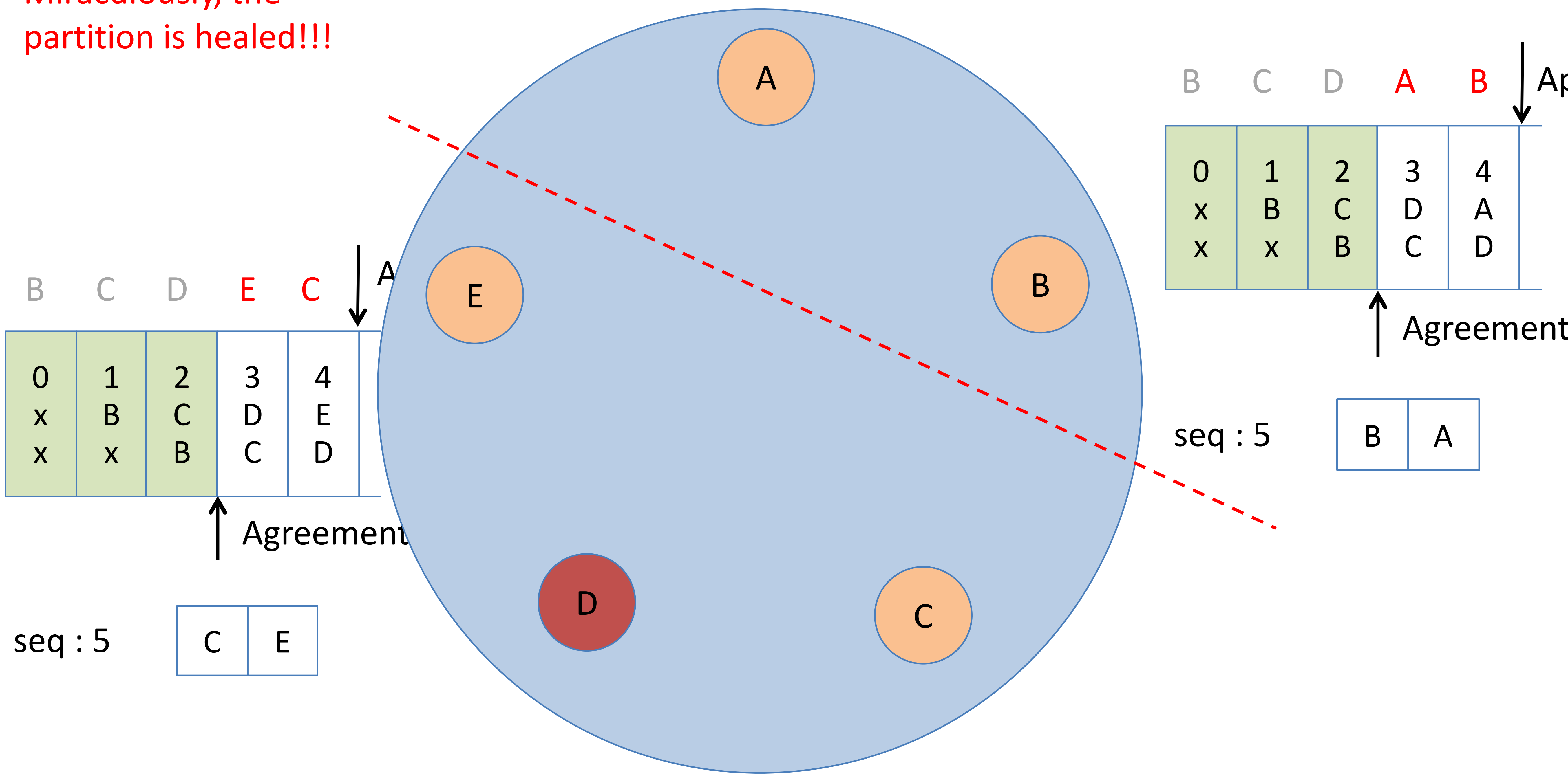
Handling Errors?

D now has the token



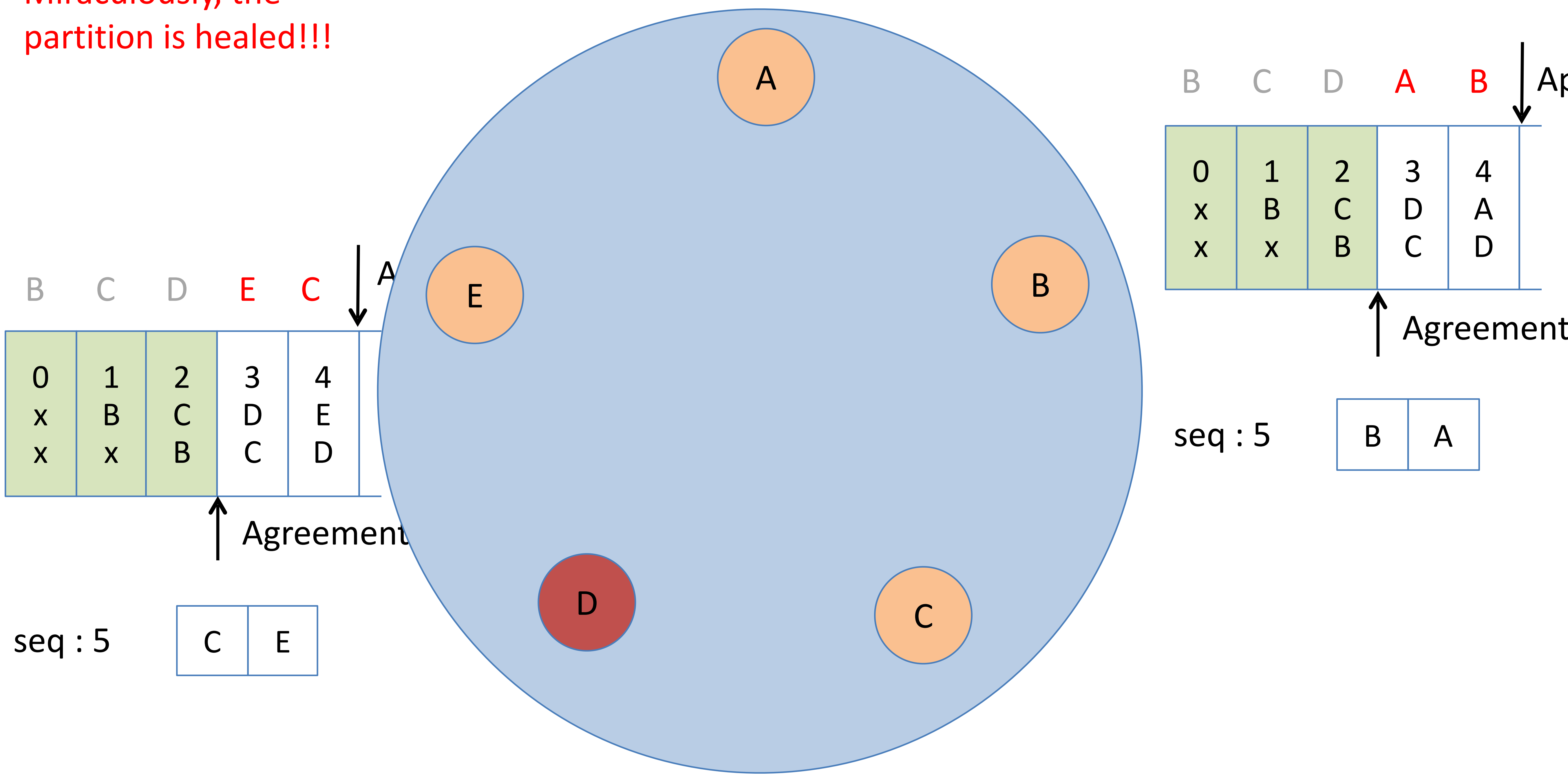
Handling Errors?

Miraculously, the partition is healed!!!



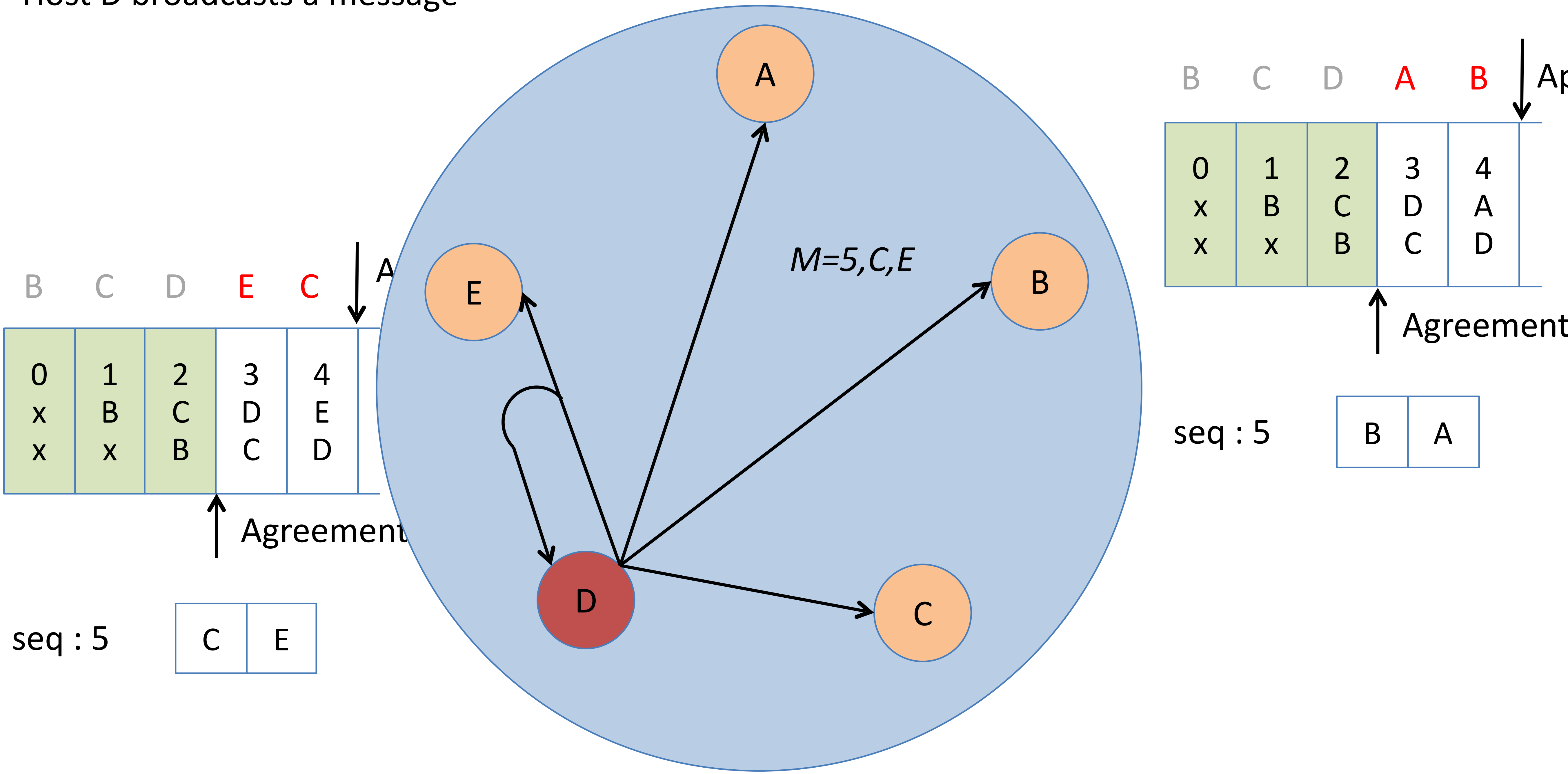
Handling Errors?

Miraculously, the partition is healed!!!



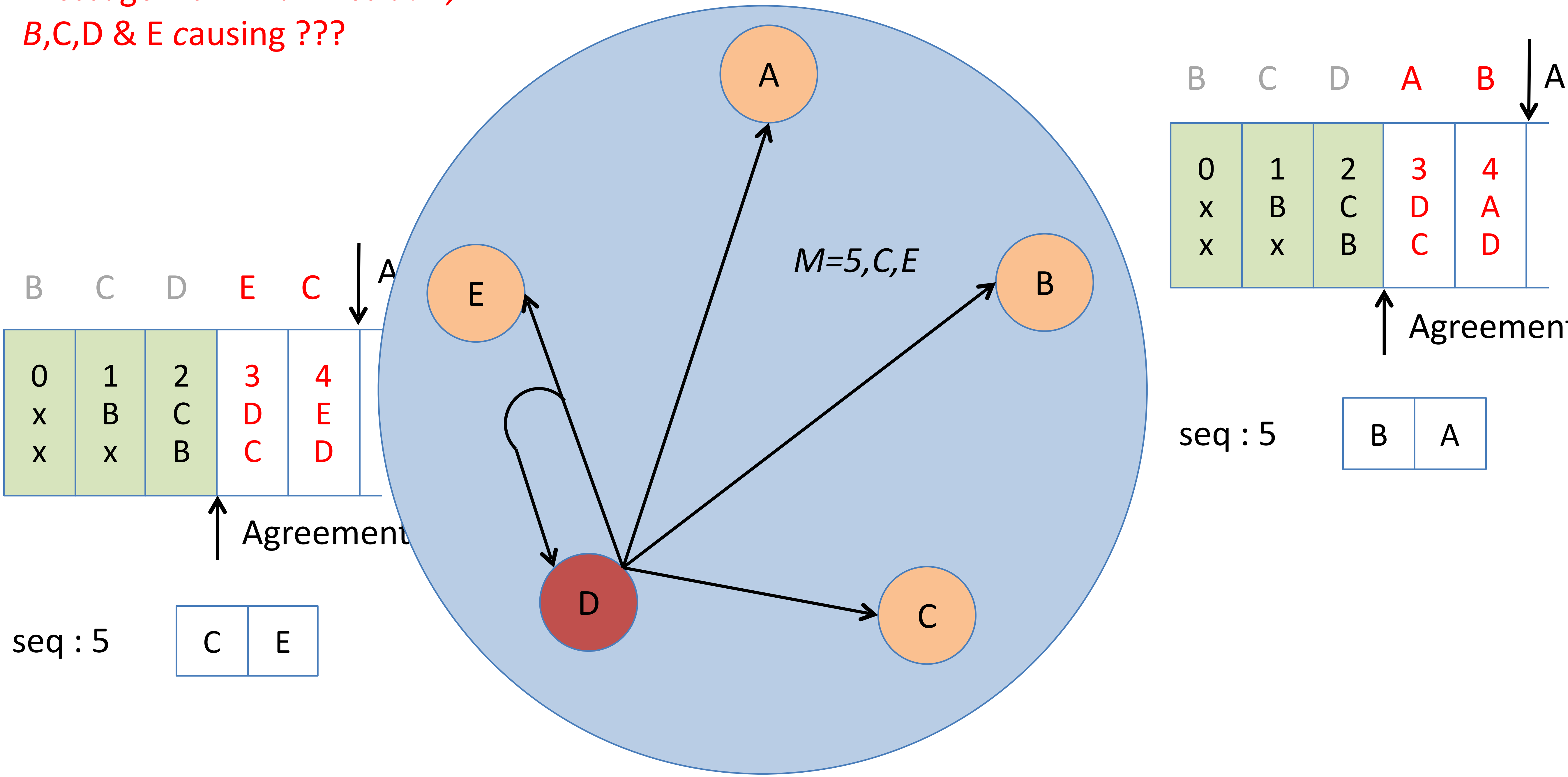
Handling Errors?

Host D broadcasts a message



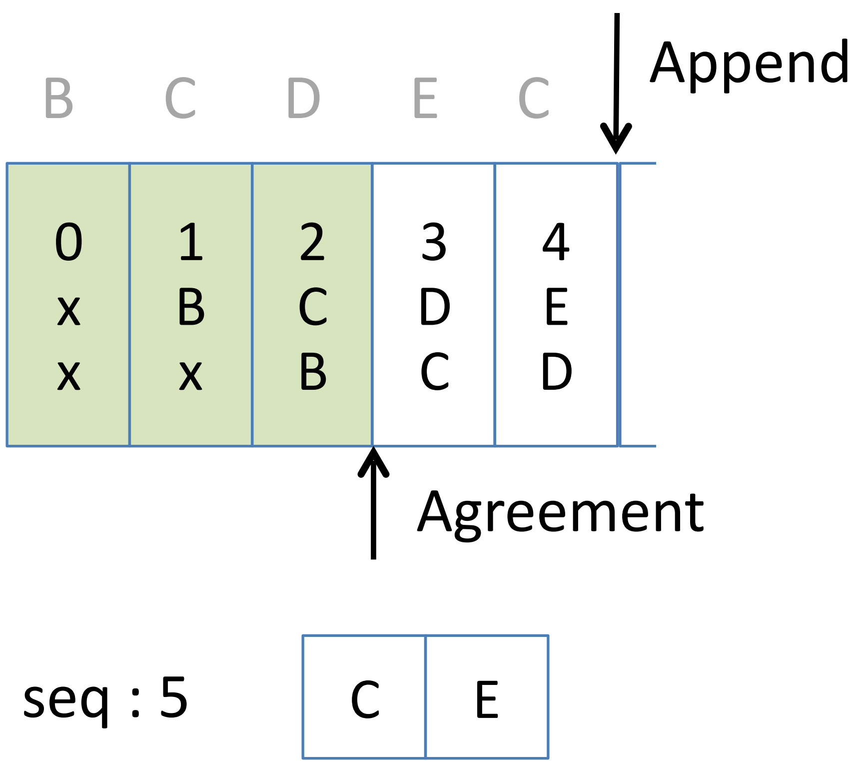
Handling Errors?

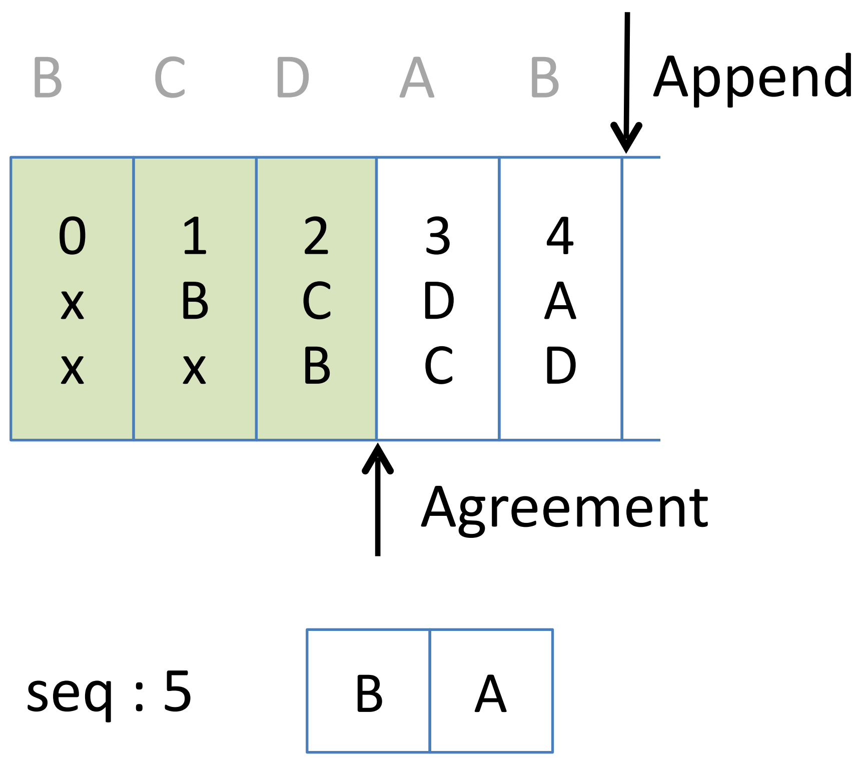
Message from *D* arrives at *A*, *B*,C,D & E *causing* ???



Handling Errors?

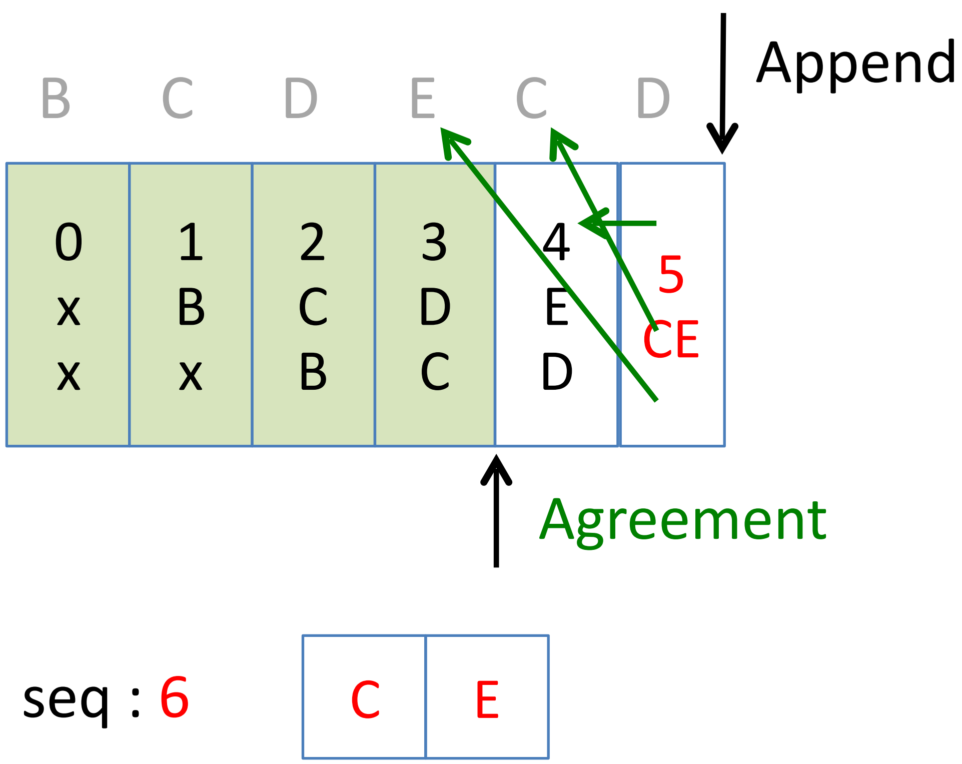
Message from *D* arrives at *A*,
B,C,D & E *causing* ???

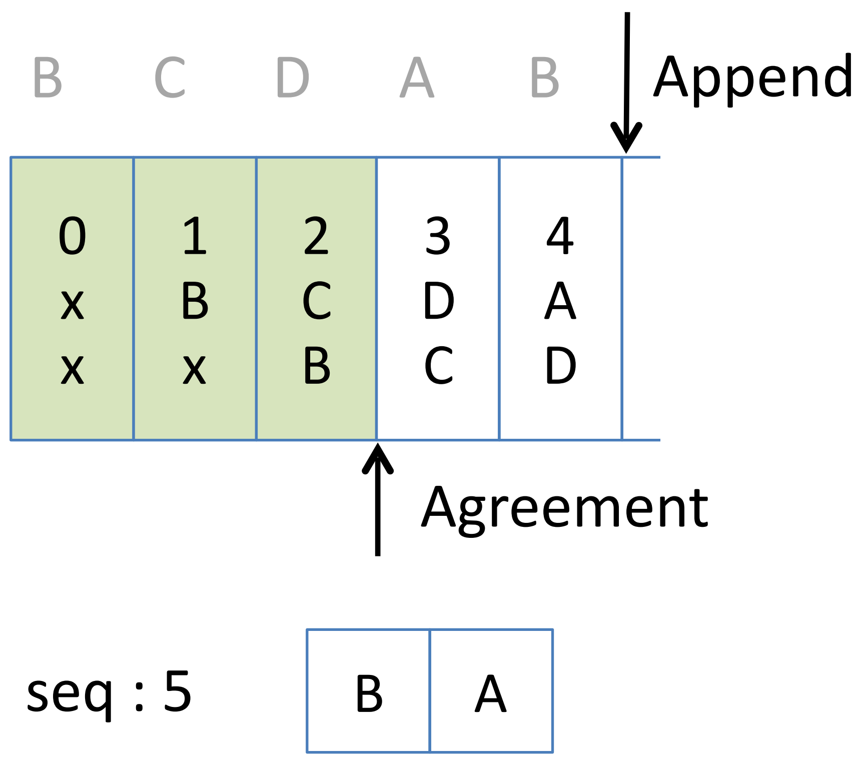




Handling Errors?

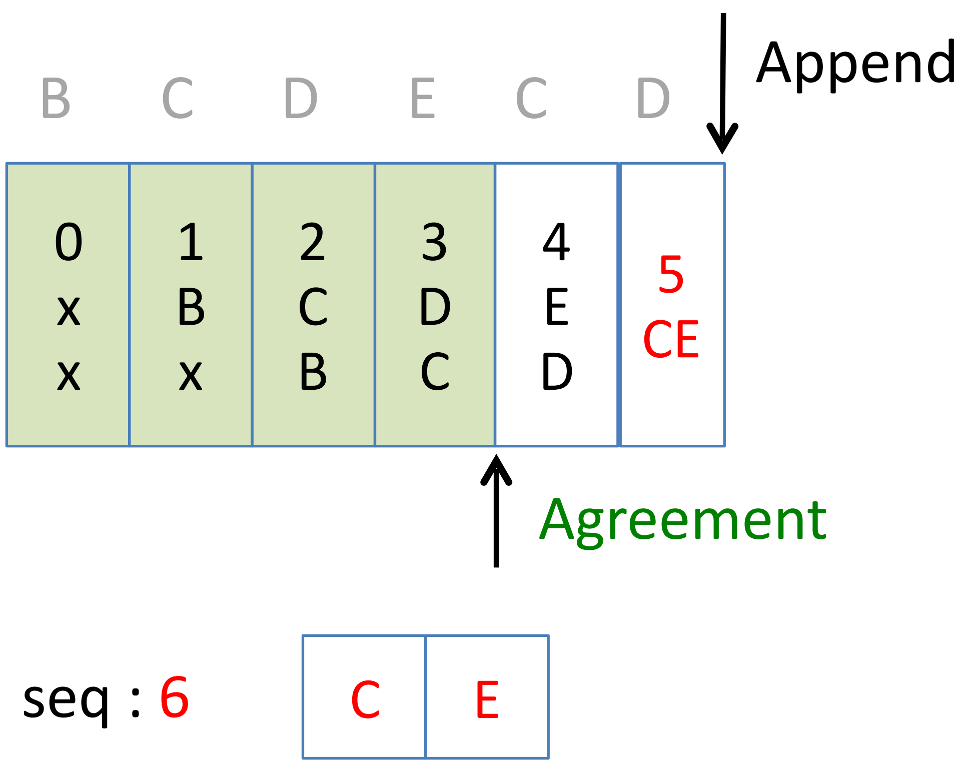
Message from *D* arrives at *A*, *B*,C,D & E *causing* ???

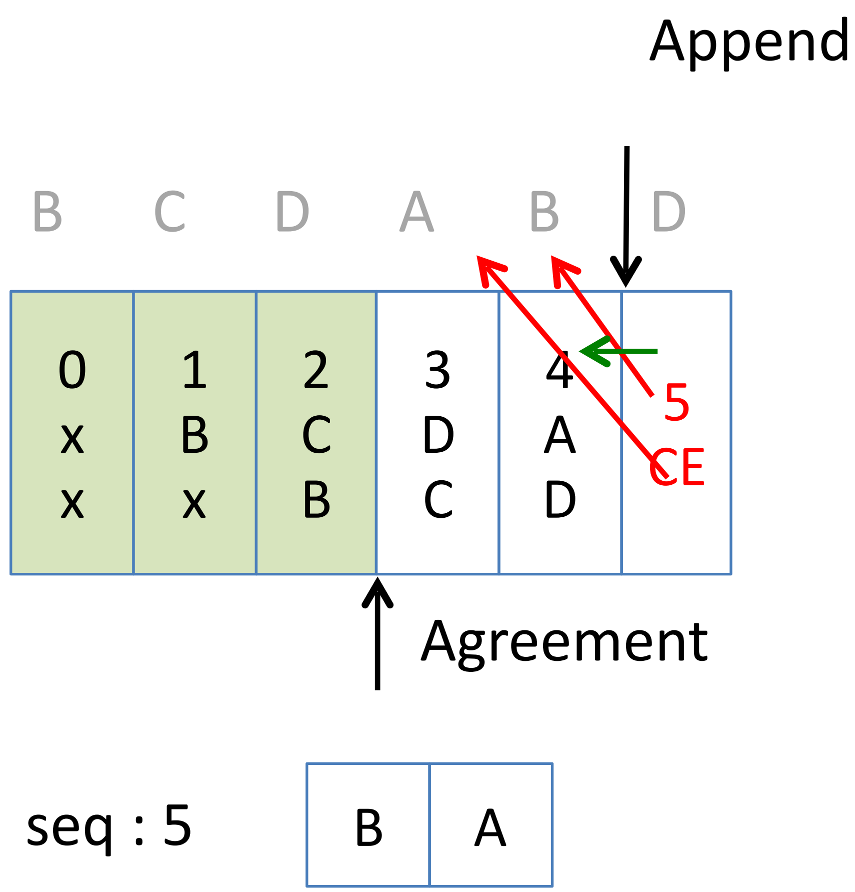




Handling Errors?

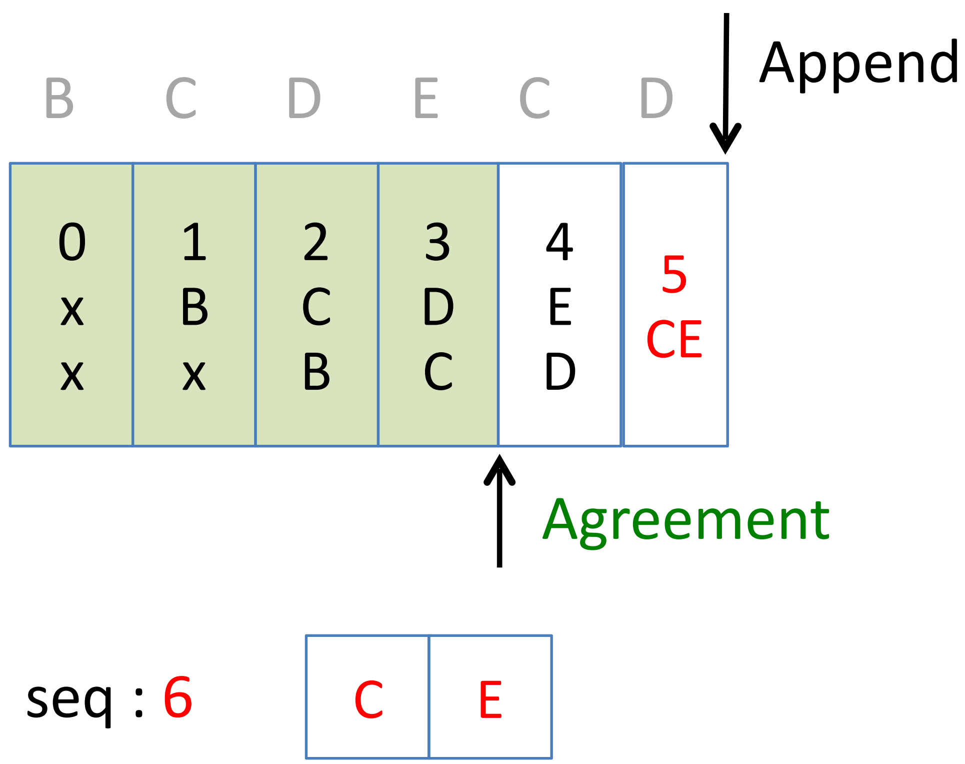
Message from *D* arrives at *A, B*,C,D & E *causing* ???

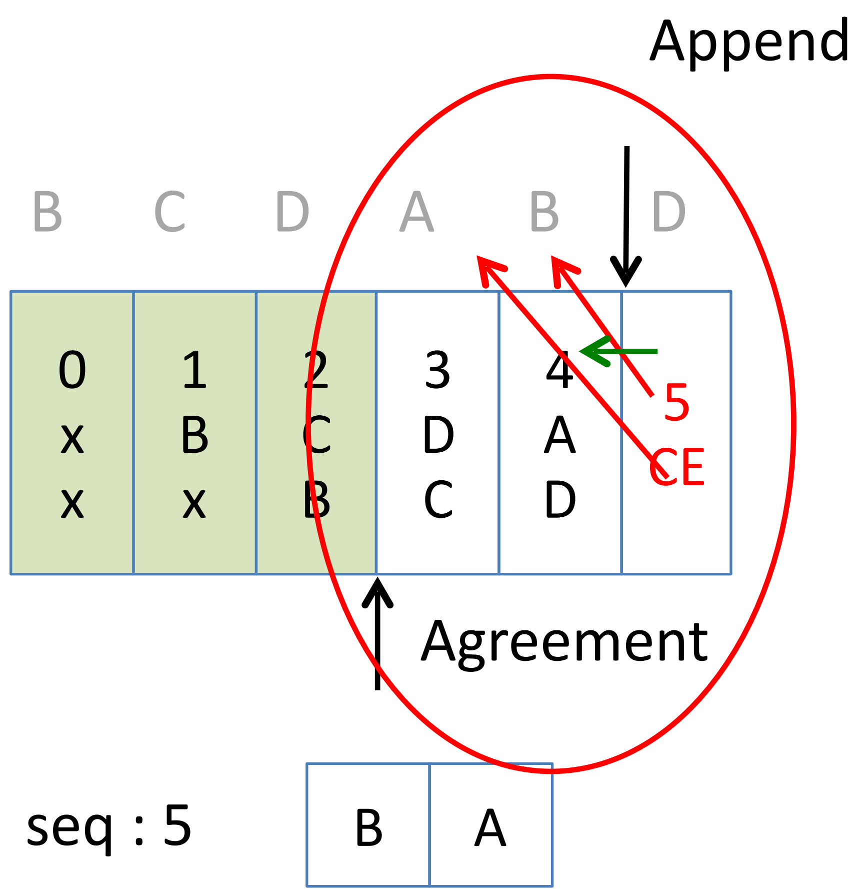




Handling Errors?

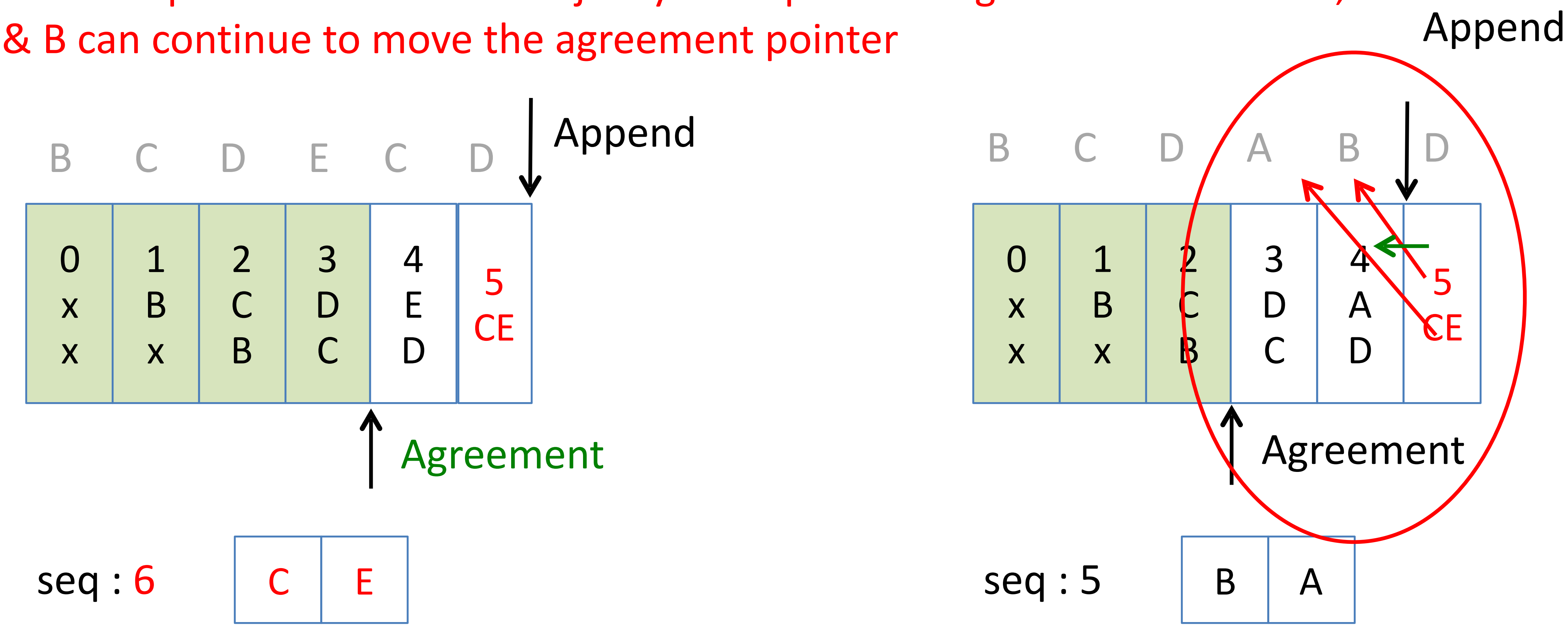
Message from *D* arrives at *A, B*,C,D & E *causing*
-update and agreement to C, D & E
-error detection for A & B





Handling Errors?

Hosts A &B must now use the out of band network to query C,D & E about their log state for sequence 3-5. Once a majority of response are gathered is reached, host A & B can continue to move the agreement pointer



Handling Errors?

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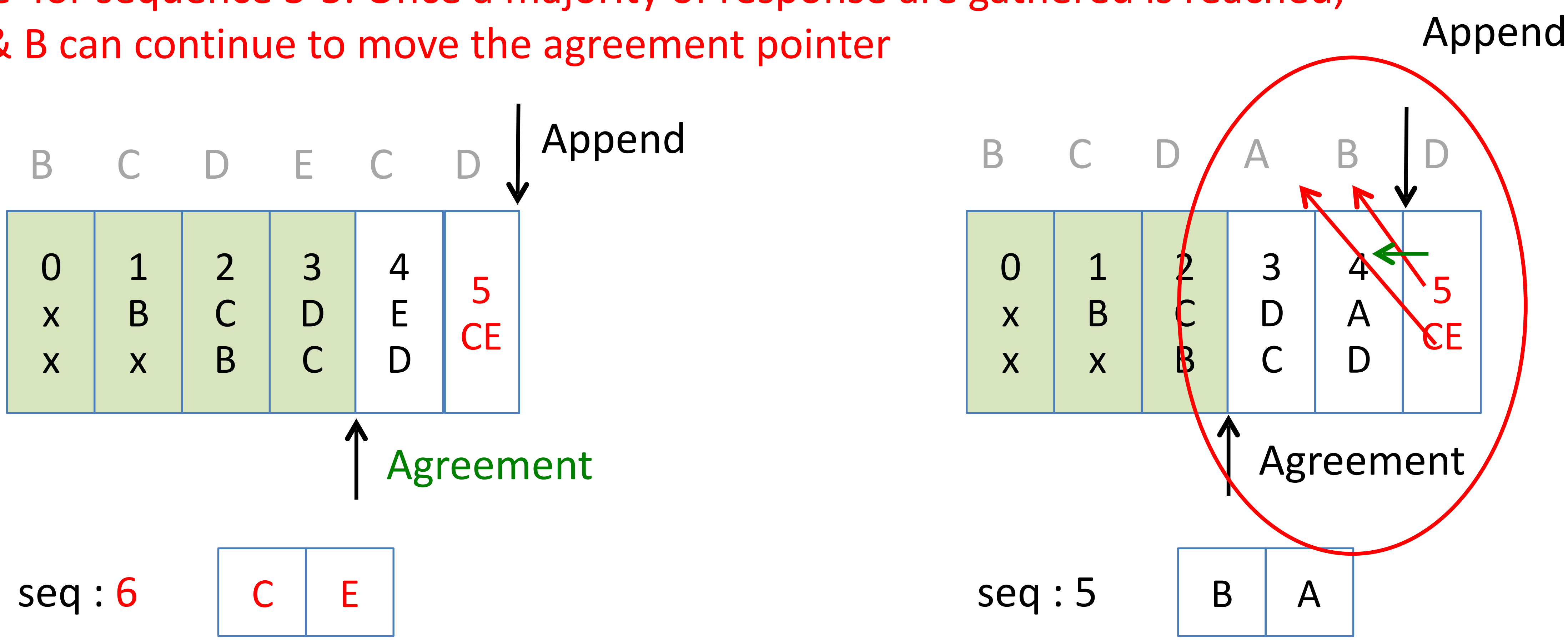

NB: New messages can be added to the log at the append pointer, but the agreement pointer cannot move until consensus has been reached