Distributed Systems

CS425/ECE428

Feb 15 2023

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Acknowledgements for some of the materials: Indy Gupta and Nikita Borisov

Today's agenda

- **Wrap up Multicast**
  - Chapter 15.4
  - Tree-based multicast and Gossip
- **Mutual Exclusion**
  - Chapter 15.2

Recap: Ordered Multicast

- **FIFO ordering:** If a correct process issues multicast(*g*,*m*) and then multicast(*g*,*m'*), then every correct process that delivers *m'* will have already delivered m.

- **Causal ordering:** If multicast(*g*,*m*) → multicast(*g*,*m'*) then any correct process that delivers *m'* will have already delivered *m*.
  - Note that → counts multicast messages **delivered** to the application, rather than all network messages.

- **Total ordering**: If a correct process delivers message *m* before *m'*, then any other correct process that delivers *m'* will have already delivered *m*.

ISIS algorithm: failures

- What happens if sender fails while multicasting a message?
- What happens if sender fails while multicasting the final priority of a message?
- What happens if a process fails before sending the proposed priority for a message?
- What happens if a process fails after sending the proposed priority for a message?

Ordered Multicast

- FIFO ordering
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- Causal ordering
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Implementing causal order multicast

- Similar to FIFO Multicast
  - What you send with a message differs.
  - Updating rules differ.

- Each receiver maintains a vector of per-sender sequence numbers (integers)
  - Processes P*1* through P*N.*
  - P*i* maintains a vector of sequence numbers P*i*[1…N] (initially all zeroes).
  - P*i*[*j*] is the latest sequence number P*i* has received from P*j.*

Implementing causal order multicast

- *CO-multicast(g,m) at Pj:*

  set $Pj[j] = Pj[j] + 1$

  piggyback **entire vector** $Pj[1\ldots N]$ with m.

  B-multicast(g,{m, *Pj[1 … N]*})

- *On B-deliver({m, V[1..N]}) at Pi from Pj:* If Pi receives a multicast from Pj with sequence vector V[1…N], buffer it until both:
  1. This message is the next one P*i* is expecting from P*j*, i.e.,

     $V[j] = Pi[j] + 1$

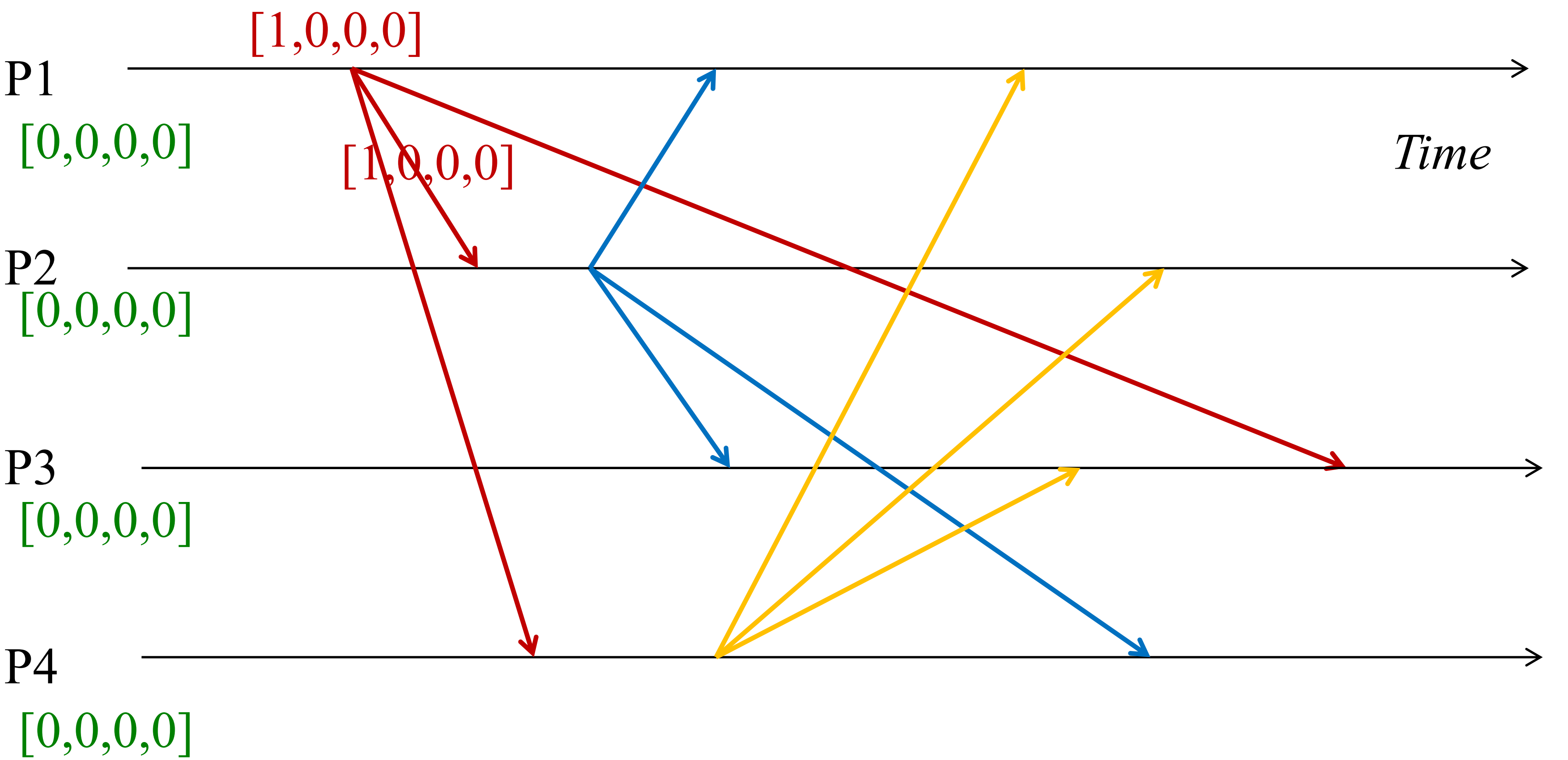
  2. All multicasts, anywhere in the group, which happened-before m have been received at P*i*, i.e.,

     For all $k \neq j$: $V[k] \leq Pi[k]$

  When above two conditions satisfied,

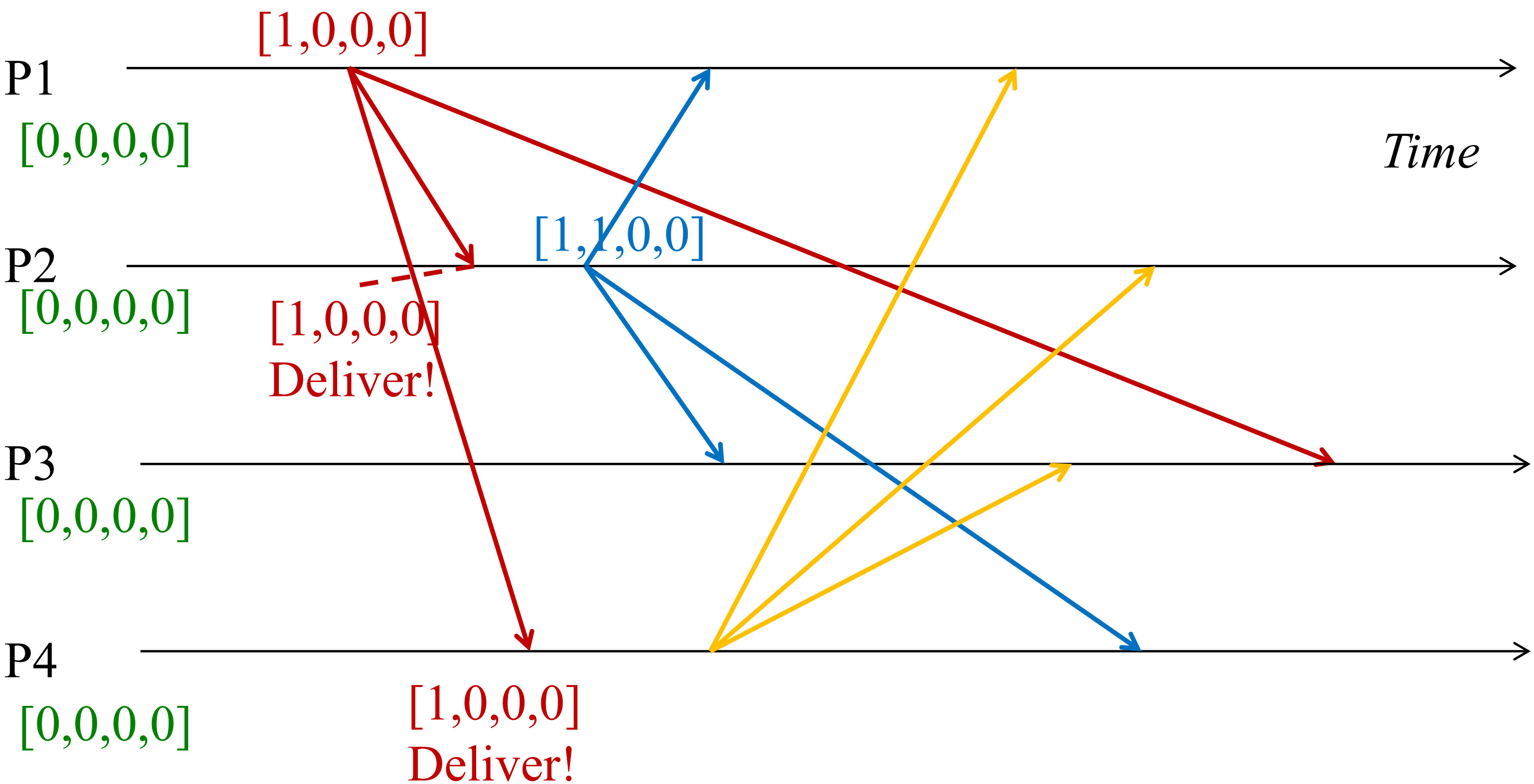
  CO-deliver(m) and set $Pi[j] = V[j]$

Causal order multicast execution



Self-deliveries omitted for simplicity.

Causal order multicast execution



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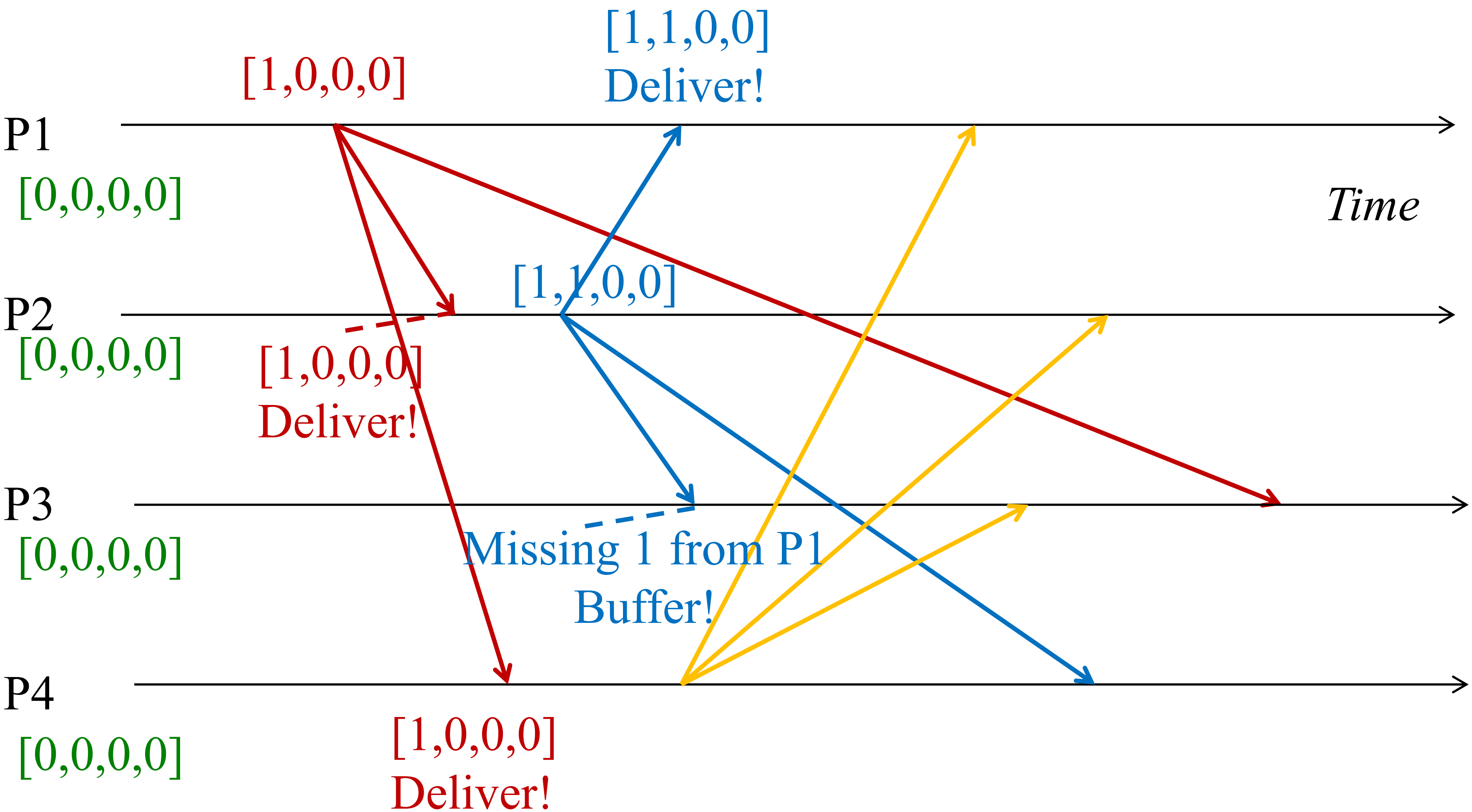

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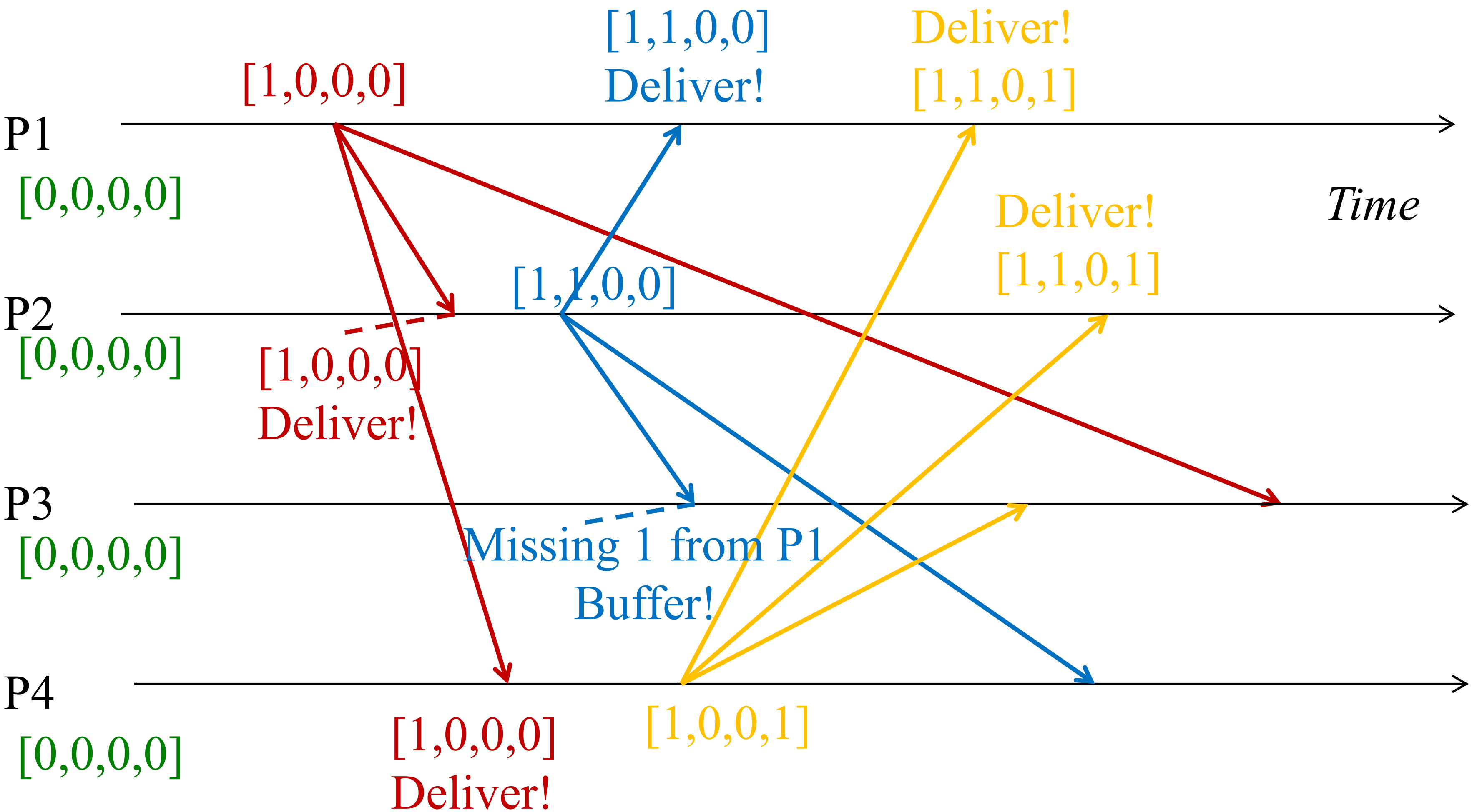

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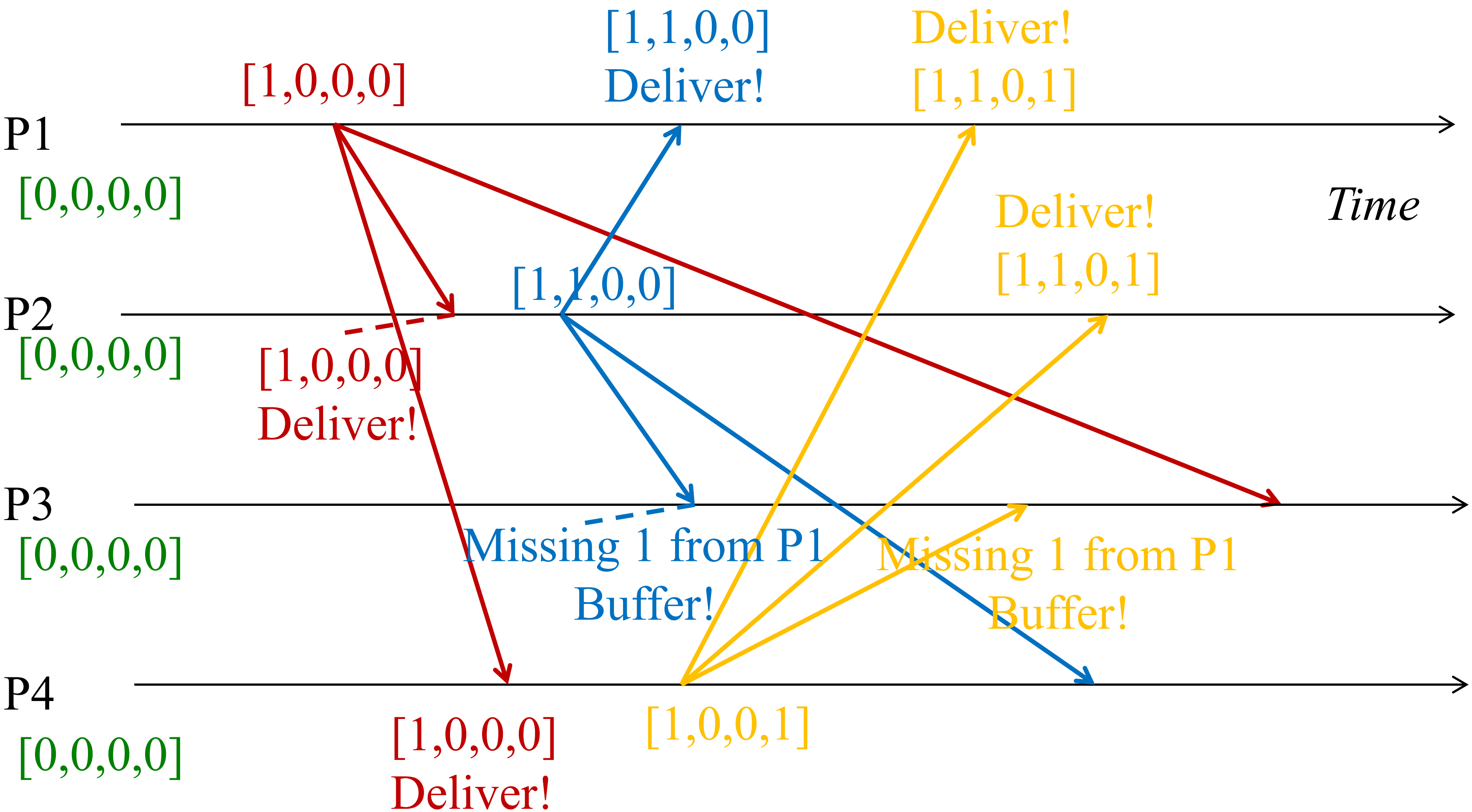

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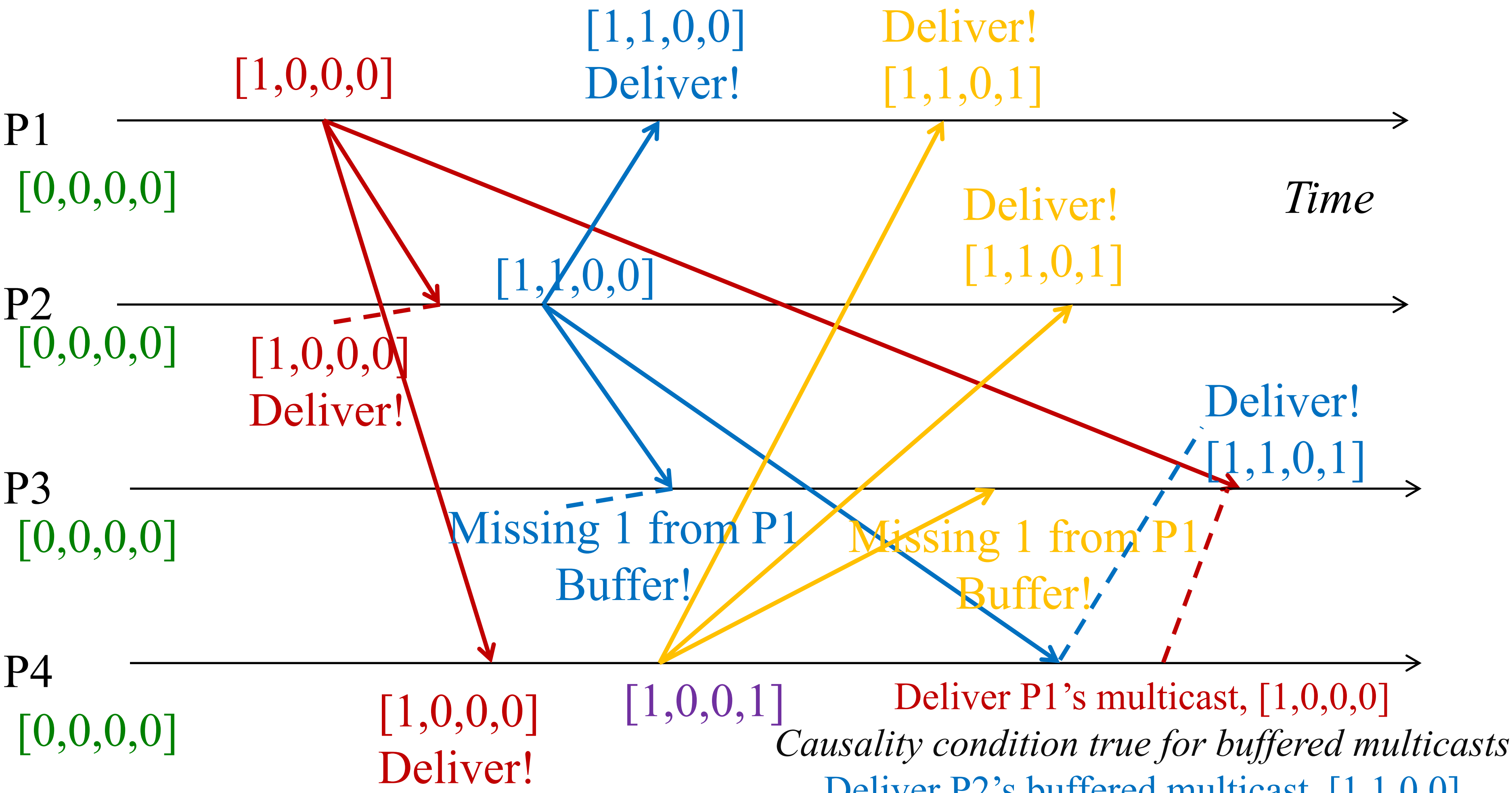

Causal order multicast implementation

- Only looks at multicast messages delivered to the application.

- Ignores causality created due to other network messages.

Ordered Multicast

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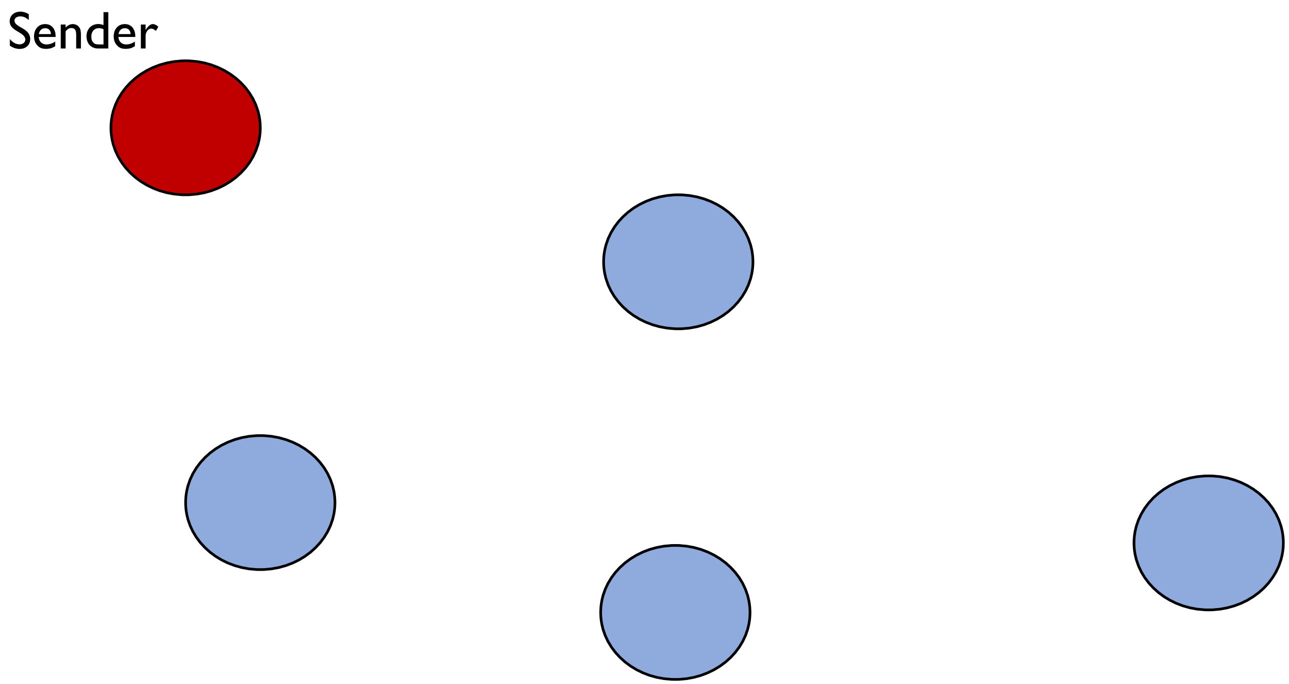
More efficient multicast mechanisms

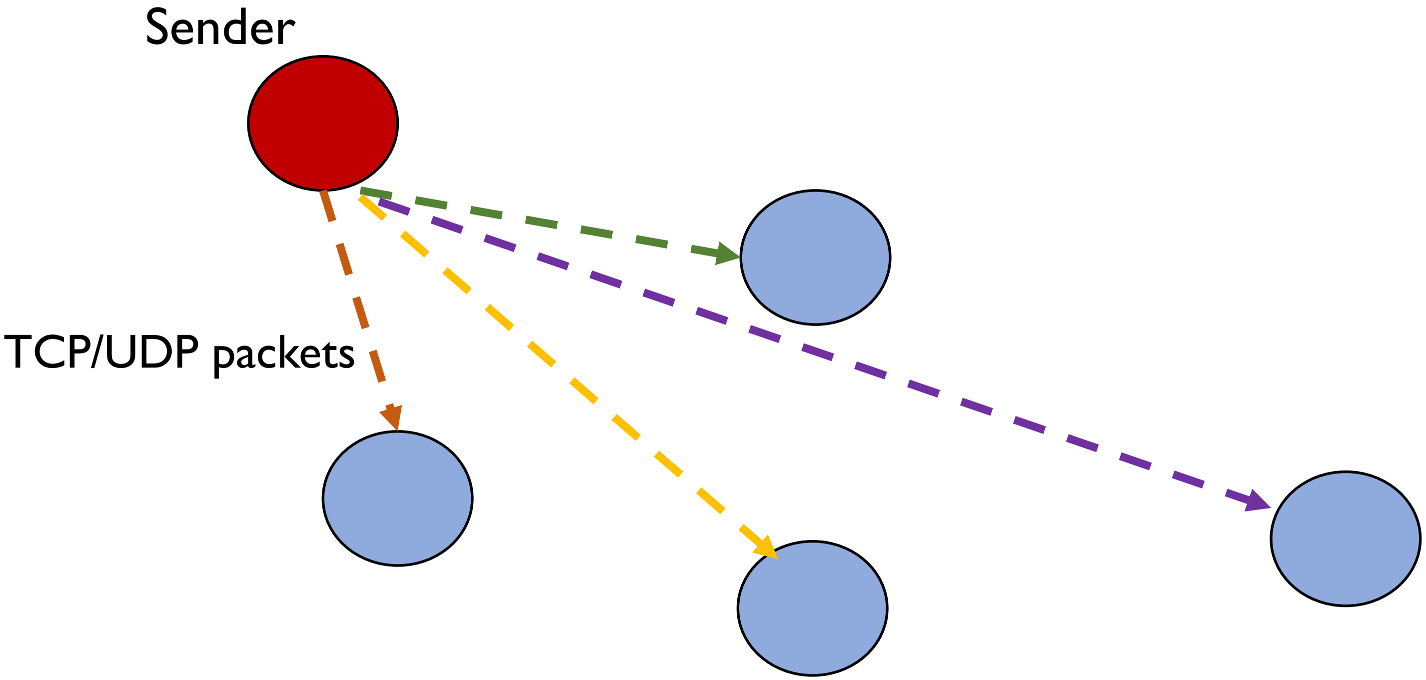
- Our focus so far has been on the application-level semantics of multicast.

- *What are some of the more efficient underlying mechanisms for a B-multicast?*

B-Multicast

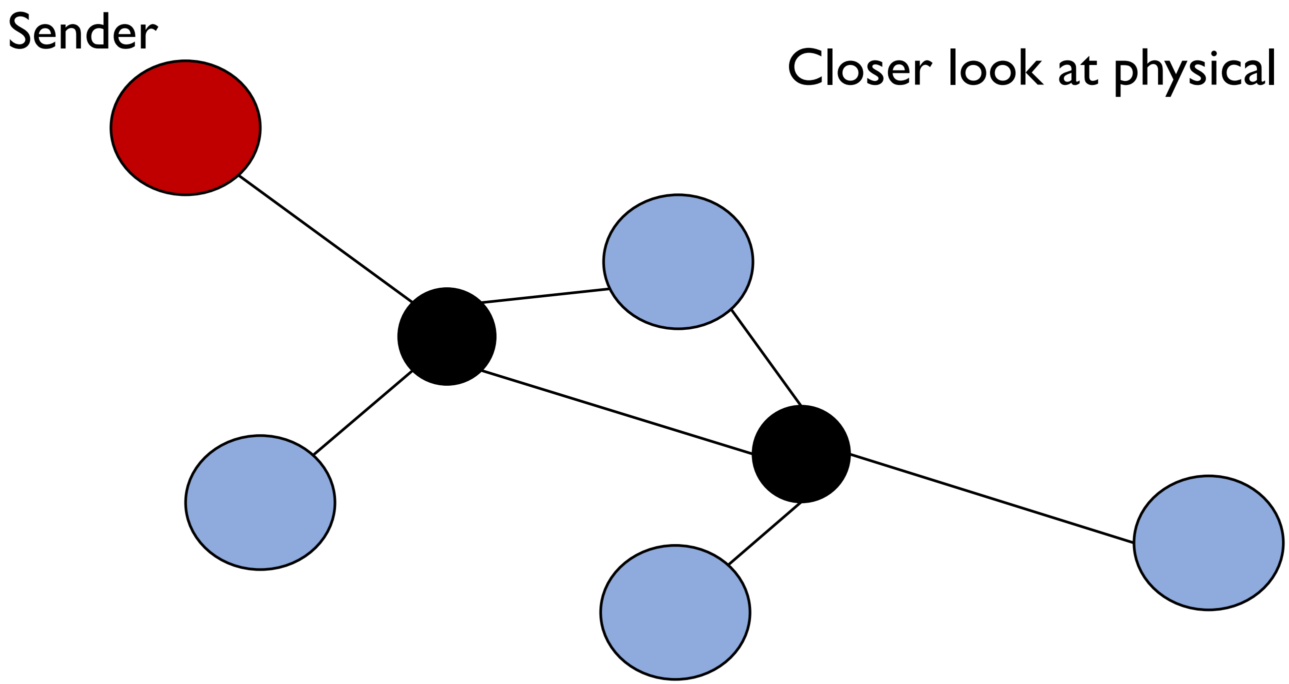


B-Multicast using unicast sends



B-Multicast using unicast sends

Closer look at physical network paths.



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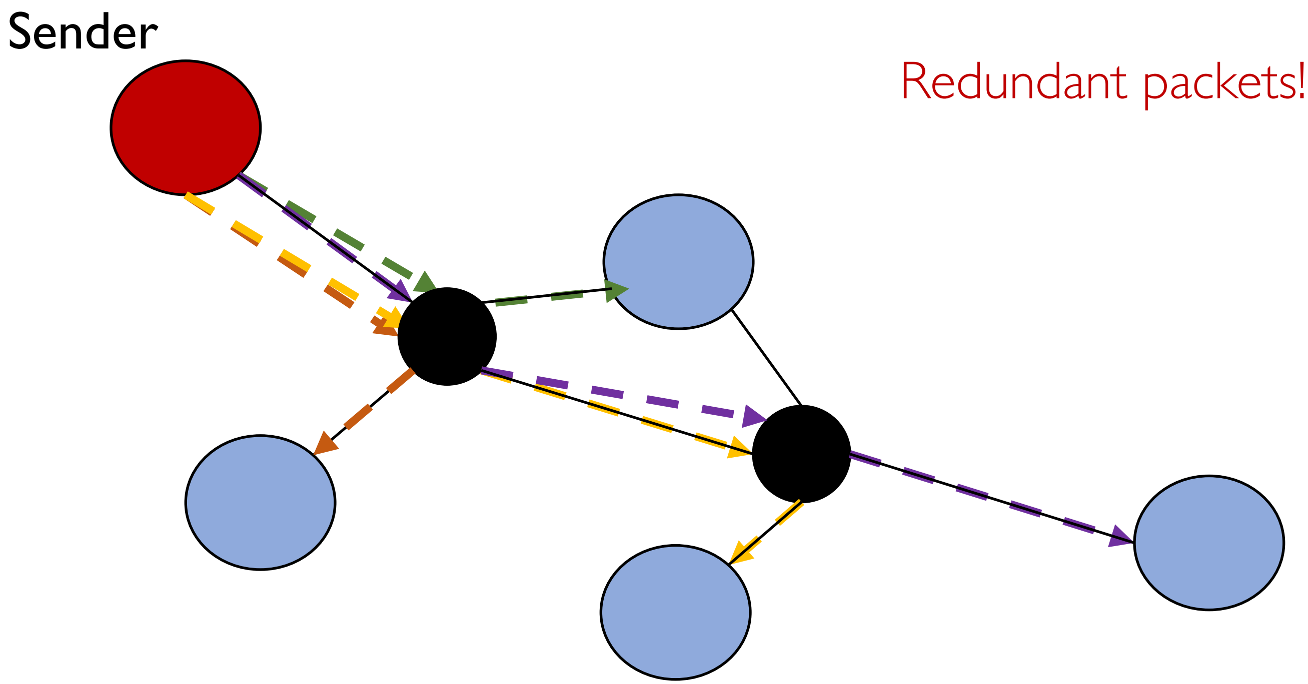

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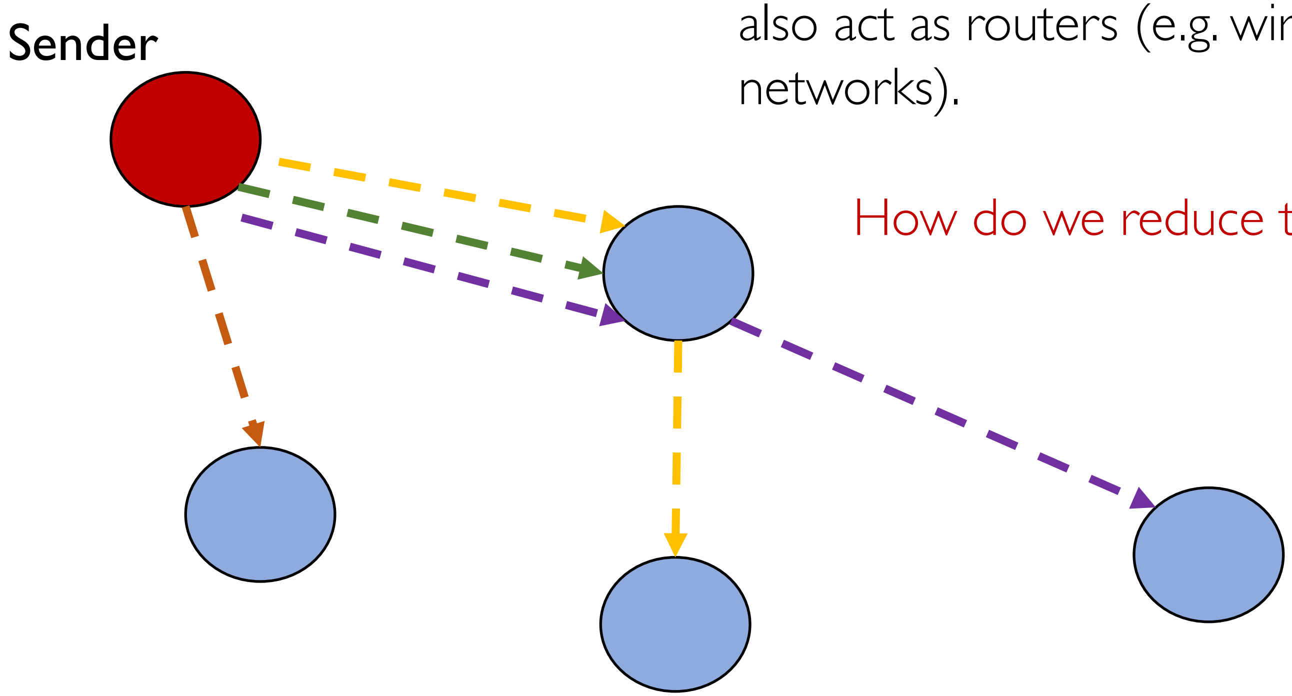
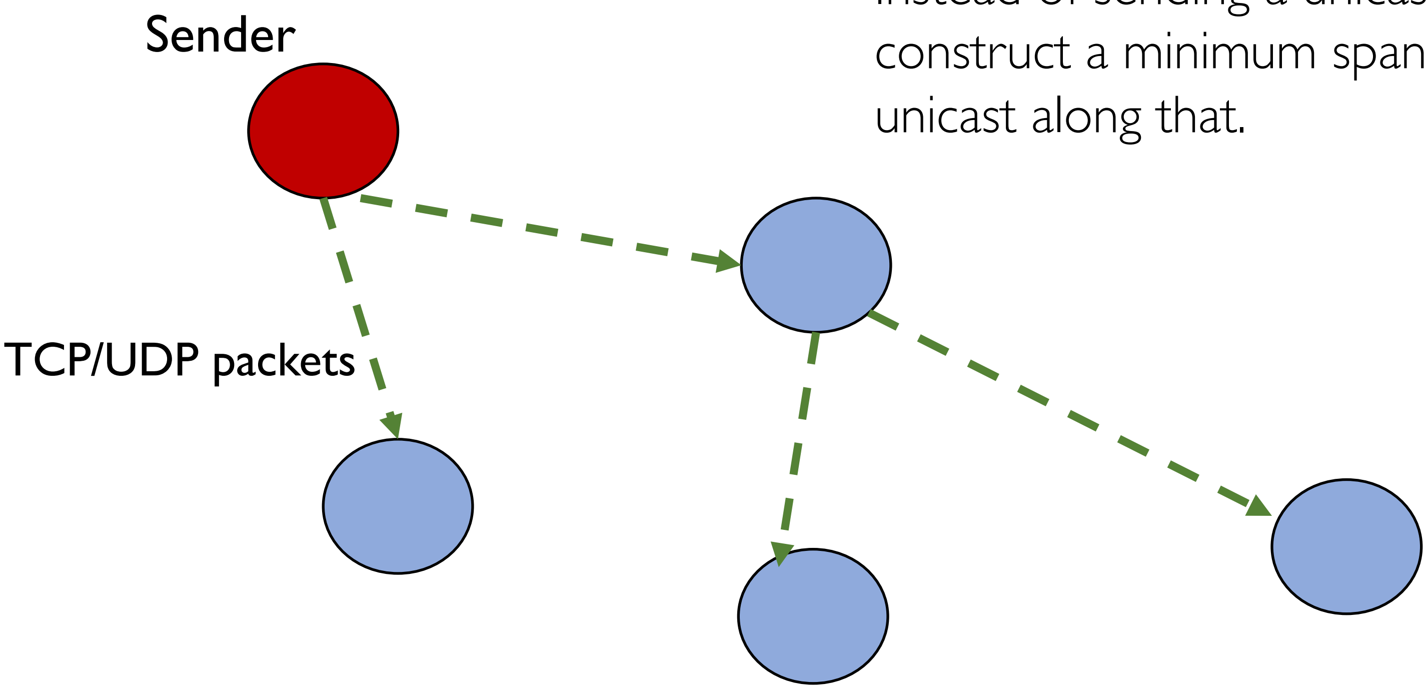


Similar redundancy when individual nodes also act as routers (e.g. wireless sensor networks).

How do we reduce the overhead?

Tree-based multicast

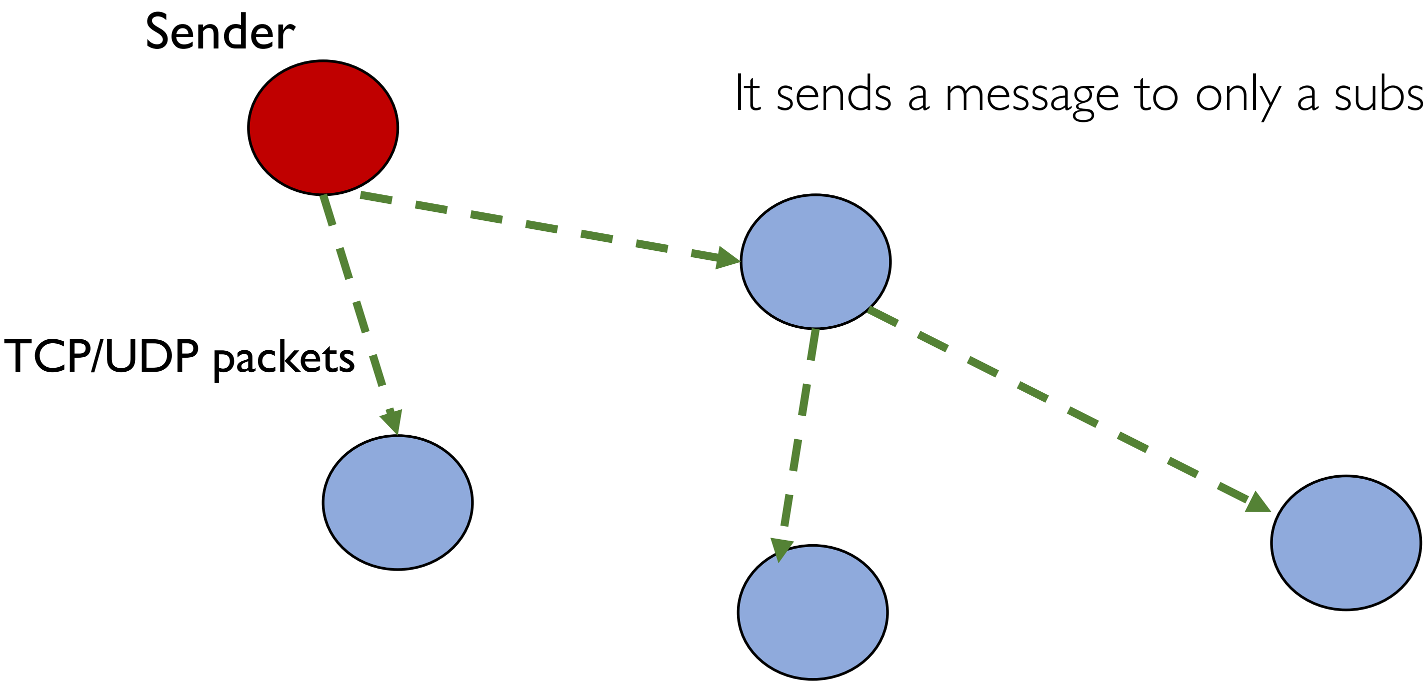
Instead of sending a unicast to all nodes, construct a minimum spanning tree and unicast along that.



Tree-based multicast

A process does not directly send messages to *all* other processes in the group.

It sends a message to only a subset of processes.



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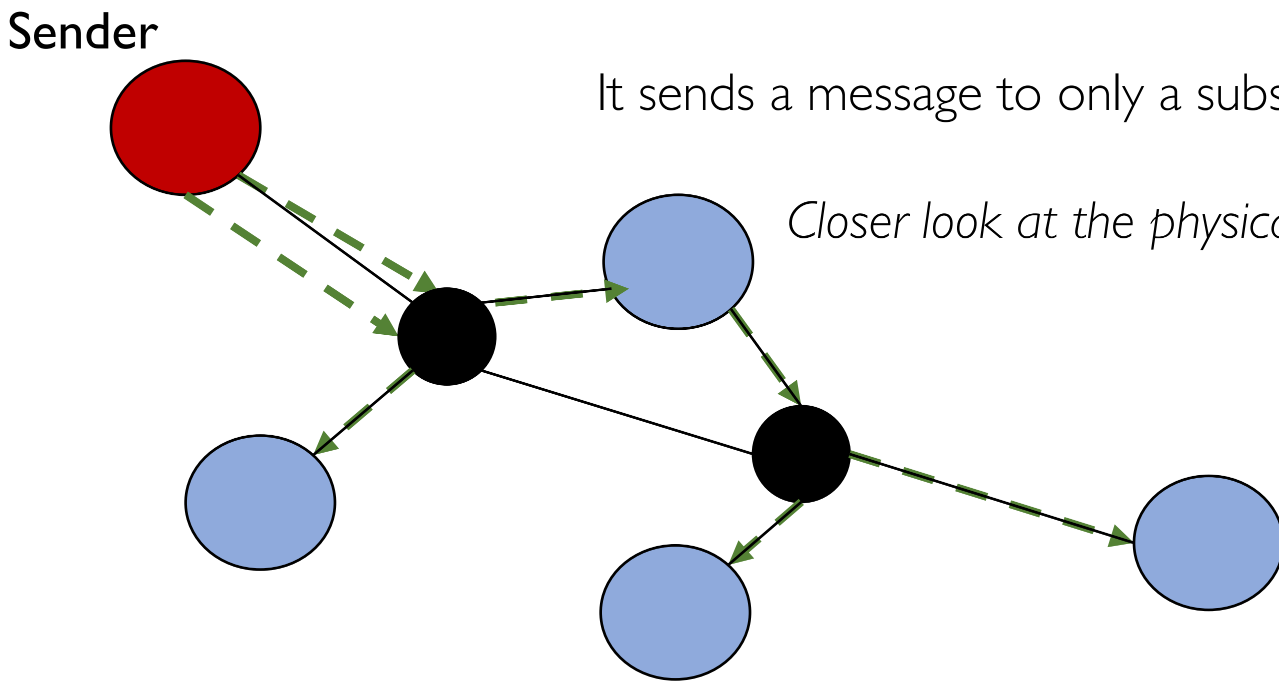
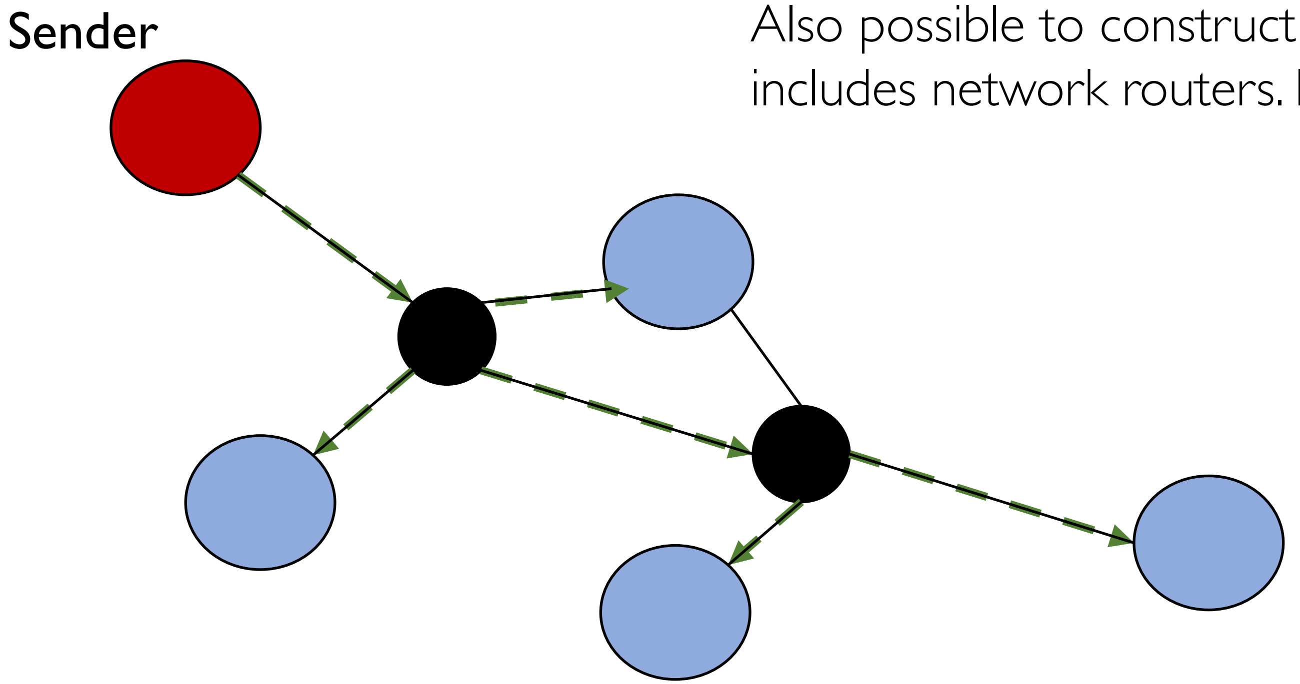
Closer look at the physical network.



Tree-based multicast

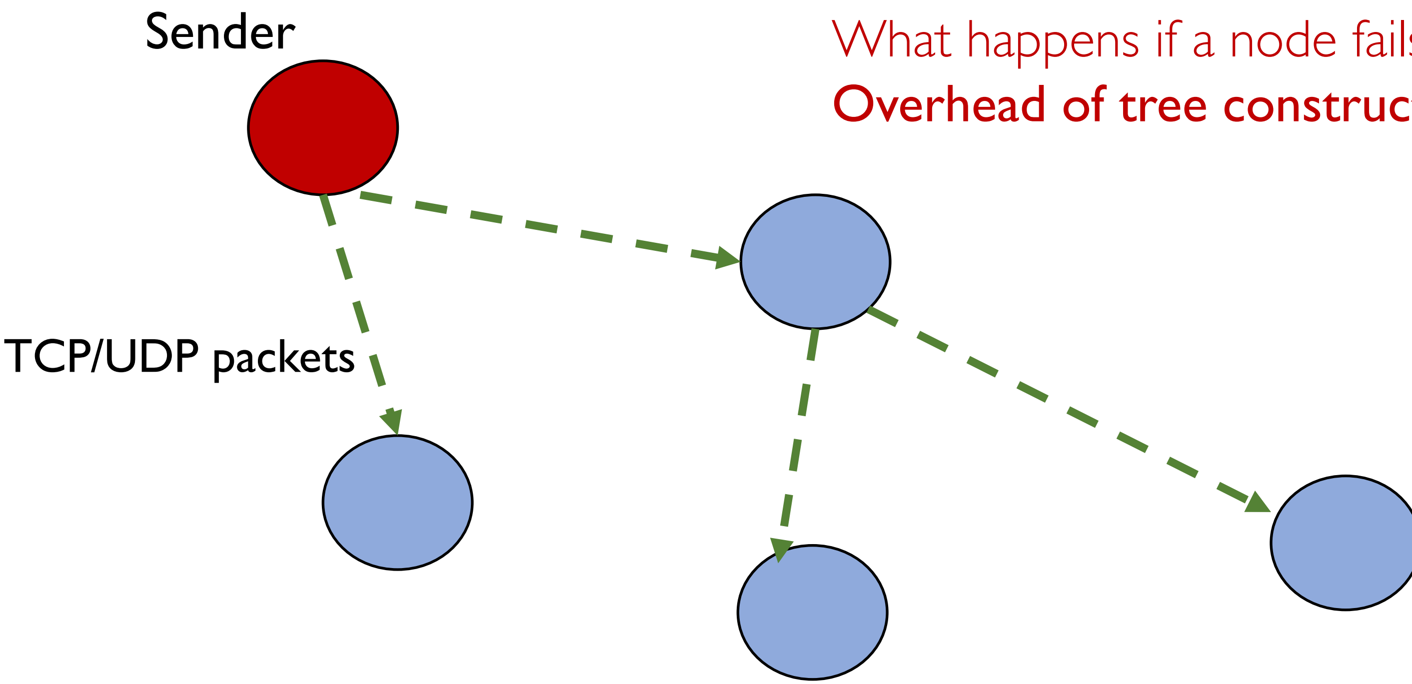


Also possible to construct a tree that includes network routers. **IP multicast!**

Tree-based multicast

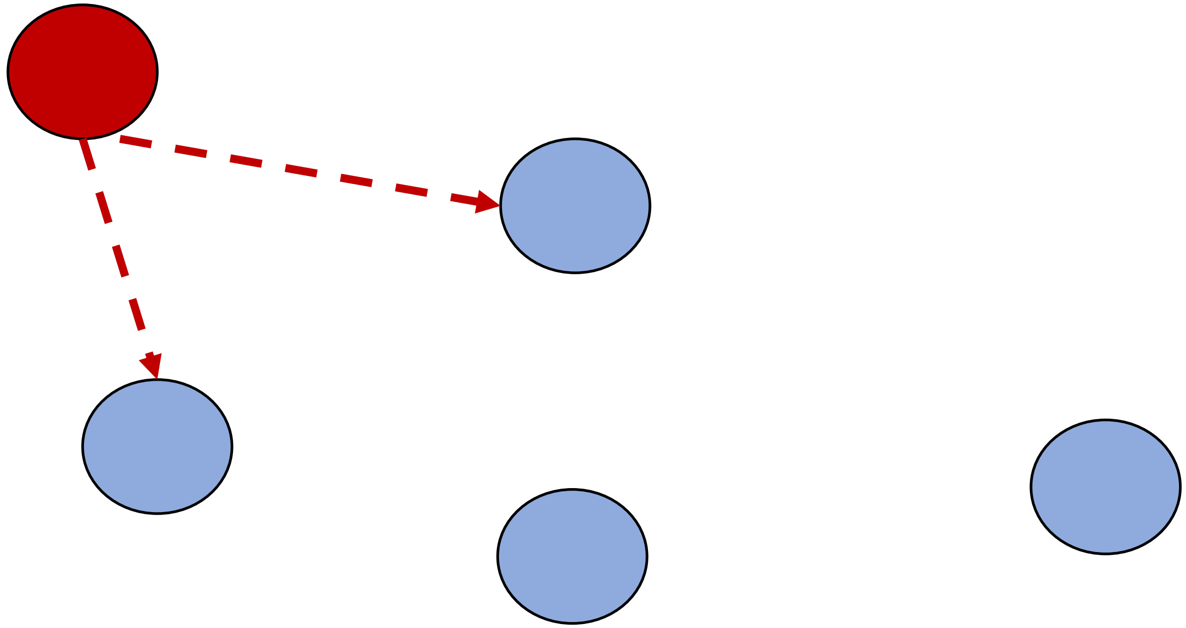
What happens if a node fails?

Overhead of tree construction and repair.



Third approach: Gossip

Transmit to b random targets.



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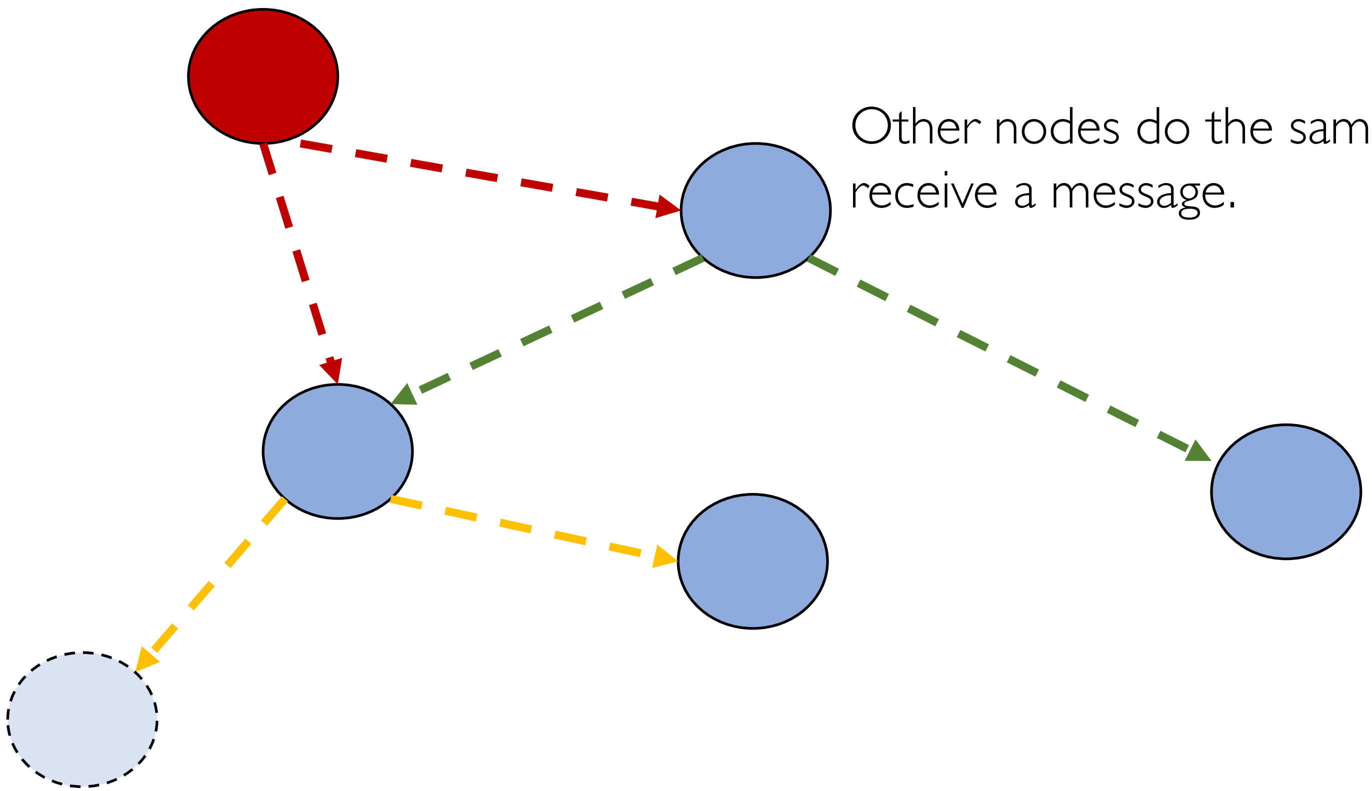

Other nodes do the same when they receive a message.

Third approach: Gossip

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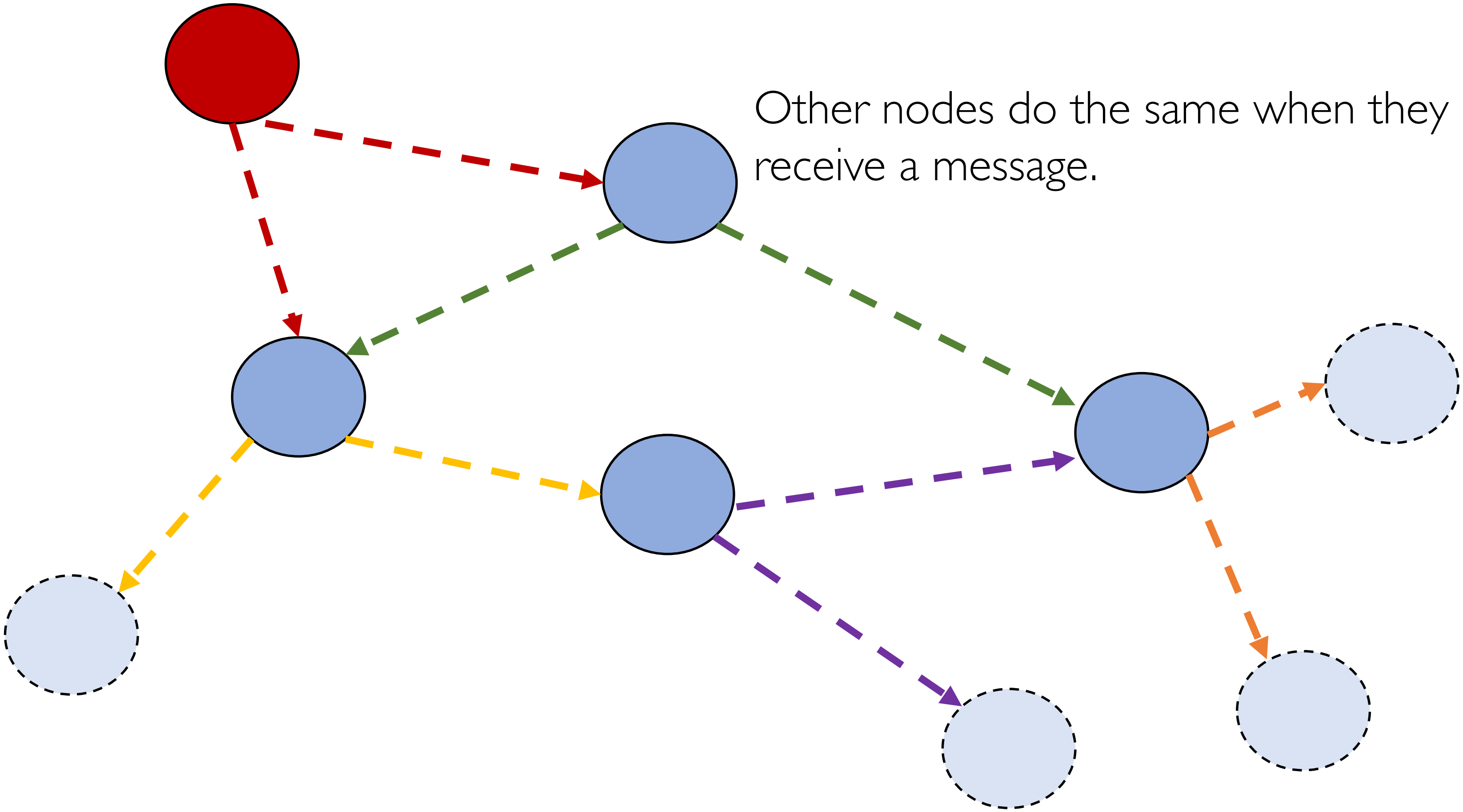


Third approach: Gossip

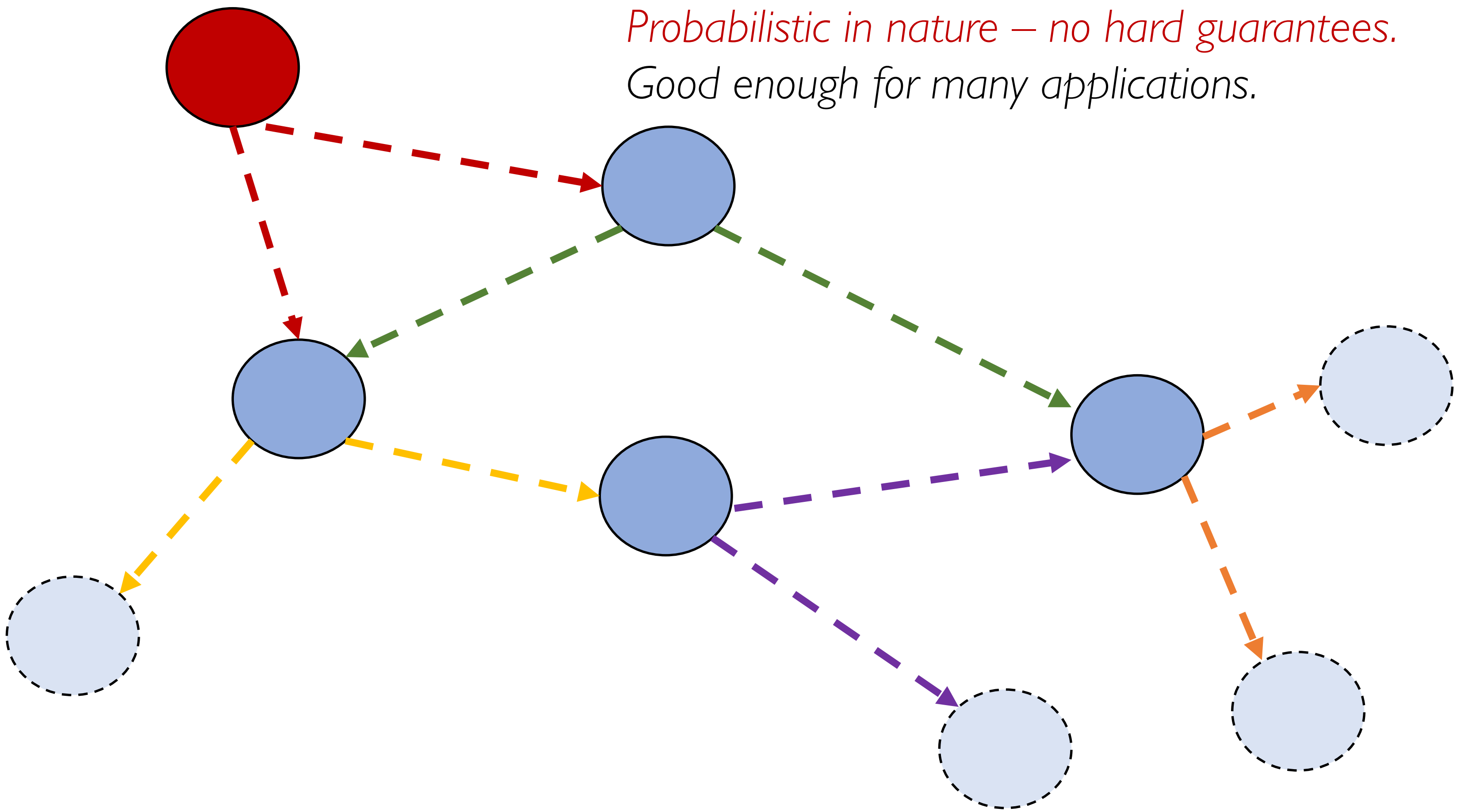
No "tree-construction" overhead.

More efficient than unicasting to all receivers.

Also known as "epidemic multicast".

Probabilistic in nature – no hard guarantees.

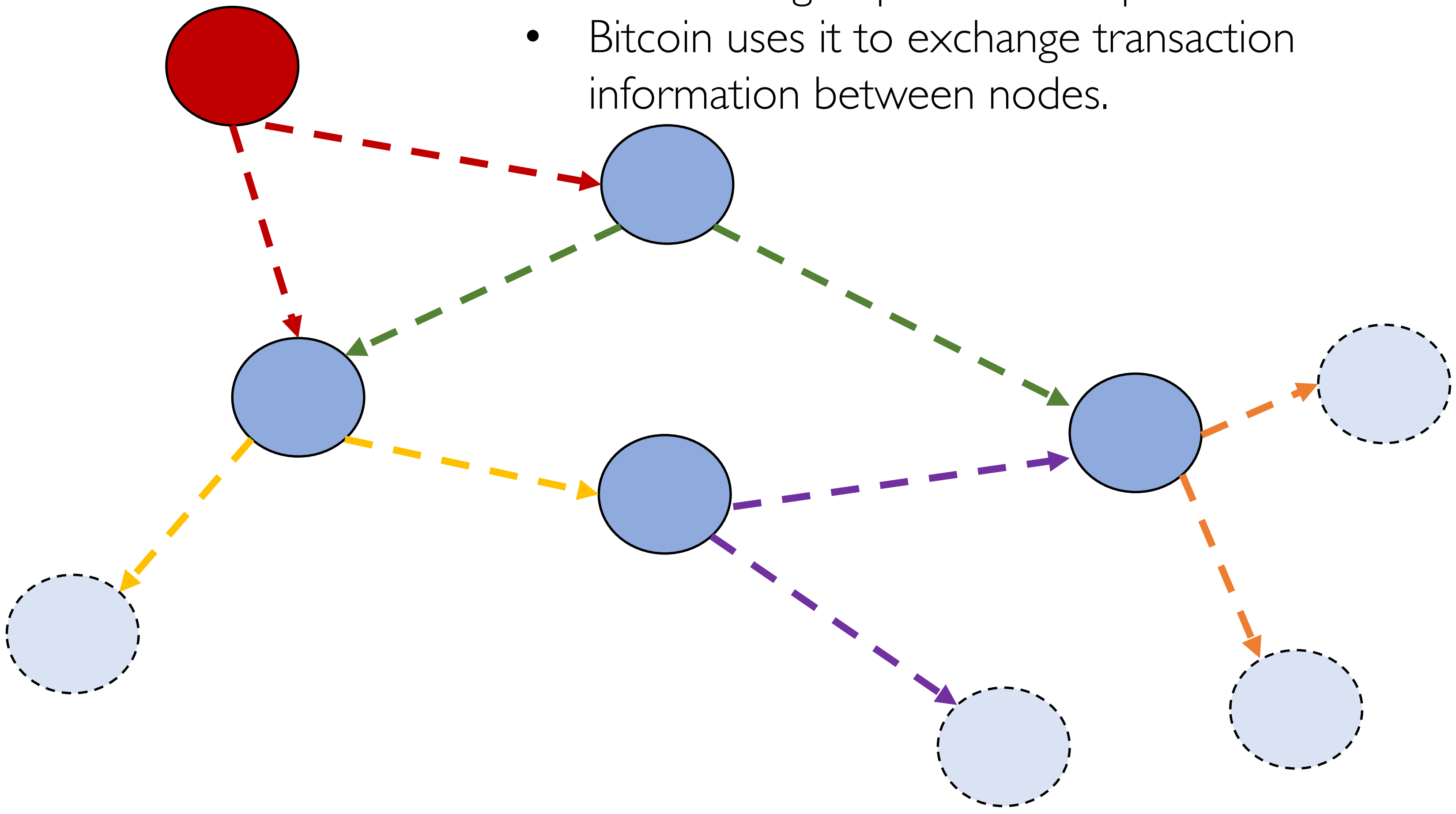
Good enough for many applications.



Third approach: Gossip

Used in many real-world systems:

- Facebook's distributed datastore uses it to determine group membership and failures.
- Bitcoin uses it to exchange transaction information between nodes.



Multicast Summary

- Multicast is an important communication mode in distributed systems.
- Applications may have different requirements:
  - Basic
  - Reliable
  - Ordered: FIFO, Causal, Total
  - Combinations of the above.
- Underlying mechanisms to spread the information:
  - Unicast to all receivers.
  - Tree-based multicast, and gossip: sender unicasts messages to only a subset of other processes, and they spread the message further.
  - Gossip is more scalable and more robust to process failures.

Today's agenda

- Wrap up Multicast
  - Chapter 15.4
  - Tree-based multicast and Gossip
- Mutual Exclusion
  - Chapter 15.2
- Goal: reason about ways in which different processes in a distributed system can safely manipulate shared resources.

Why Mutual Exclusion?

- Bank's Servers in the Cloud: Two of your customers make simultaneous deposits of $10,000 into your bank account, each from a separate ATM.
  - Both ATMs read initial amount of $1000 concurrently from the bank's cloud server
  - Both ATMs add $10,000 to this amount (locally at the ATM)
  - Both write the final amount to the server
  - What's wrong?

Why Mutual Exclusion?

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  - Both ATMs read initial amount of $1000 concurrently from the bank's cloud server
  - Both ATMs add $10,000 to this amount (locally at the ATM)
  - Both write the final amount to the server
  - You lost $10,000!
- The ATMs need *mutually exclusive* access to your account entry at the server
  - or, mutually exclusive access to executing the code that modifies the account entry.

More uses of mutual exclusion

- Distributed file systems
  - Locking of files and directories
- Accessing objects in a safe and consistent way
  - Ensure at most one server has access to object at any point of time
- In industry
  - Chubby is Google's locking service

Problem Statement for mutual exclusion

- ***Critical Section*** **Problem:**
  - Piece of code (at all processes) for which we need to ensure there is <u>at most one process</u> executing it at any point of time.

- Each process can call three functions
  - enter() to enter the critical section (CS)
  - AccessResource() to run the critical section code
  - exit() to exit the critical section

Our bank example

ATM1:

```
enter();
  // AccessResource()
obtain bank amount;
add in deposit;
update bank amount;
 // AccessResource() end
exit();
```

ATM2:

```
enter();
  // AccessResource()
obtain bank amount;
add in deposit;
update bank amount;
 // AccessResource() end
exit();
```

Mutual exclusion for a single OS

- If all processes are running in one OS on a machine (or VM):
  - Semaphores
  - Mutexes
  - Condition variables
  - Monitors
  - …

Processes Sharing an OS: Semaphores

- Semaphore == an integer that can only be accessed via two special functions
- Semaphore S=1; // Max number of allowed accessors.

wait(S) (or P(S) or down(S)):

```
while(1) { // each execution of the while loop is atomic
  if (S > 0) {
        S--;
        break;
    }
}
```

enter()

signal(S) (or V(S) or up(s)):

```
S++; // atomic
```

exit()

Atomic operations are supported via hardware instructions such as compare-and-swap, test-and-set, etc.

Our bank example

ATM1:

```
enter();
  // AccessResource()
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update bank amount;
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exit();
```

ATM2:

```
enter();
  // AccessResource()
obtain bank amount;
add in deposit;
update bank amount;
 // AccessResource() end
exit();
```

Our bank example

Semaphore S=1; // shared

ATM1:

```
wait(S);   //enter
  // AccessResource()
obtain bank amount;
add in deposit;
update bank amount;
  // AccessResource() end
signal(S); // exit
```

ATM2:

```
wait(S);  //enter
  // AccessResource()
obtain bank amount;
add in deposit;
update bank amount;
  // AccessResource() end
signal(S); // exit
```

Mutual exclusion in distributed systems

- Processes communicating by passing messages.
- Cannot share variables like semaphores!
- *How do we support mutual exclusion in a distributed system?*

Mutual exclusion in distributed systems

- Our focus today: Classical algorithms for mutual exclusion in distributed systems.
  - Central server algorithm
  - Ring-based algorithm
  - Ricart-Agrawala Algorithm
  - Maekawa Algorithm

Mutual Exclusion Requirements

- Need to guarantee 3 properties:
  - Safety (essential):
    - At most one process executes in CS (Critical Section) at any time.
  - Liveness (essential):
    - Every request for a CS is granted eventually.
  - Ordering (desirable):
    - Requests are granted in the order they were made.

System Model

- Each pair of processes is connected by reliable channels (such as TCP).
- Messages sent on a channel are eventually delivered to recipient, and in FIFO (First In First Out) order.
- Processes do not fail.
  - Fault-tolerant variants exist in literature.

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Central Server Algorithm

- Elect a central server (or leader)
- Leader keeps
  - A **queue** of waiting requests from processes who wish to access the CS
  - A special **token** which allows its holder to access CS
- Actions of any process in group:
  - enter()
    - Send a request to leader
    - Wait for token from leader
  - exit()
    - Send back token to leader

Central Server Algorithm

- Leader Actions:
  - On receiving a request from process P*i*

    if (leader has token)

    Send token to P*i*

    else

    Add P*i* to queue
  - On receiving a token from process P*i*

    if (queue is not empty)

    Dequeue head of queue (say P*j*), send that process the token

    else

    Retain token

Analysis of Central Algorithm

- Safety – at most one process in CS
  - Exactly one token
- Liveness – every request for CS granted eventually
  - With *N* processes in system, queue has at most *N* processes
  - If each process exits CS eventually and no failures, liveness guaranteed
- Ordering:
  - FIFO ordering guaranteed in order of requests received at leader
  - Not in the order in which requests were sent or the order in which processes enter CS!

Analysis of Central Algorithm

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- Ordering:
  - FIFO ordering guaranteed in order of requests received at leader
  - Not in the order in which requests were sent or the order in which processes call "enter"!

Analyzing Performance

Three metrics:

- **Bandwidth**: the total number of messages sent in each *enter* and *exit* operation.
- **Client delay**: the delay incurred by a process at each enter and exit operation (when *no* other process is in CS, or waiting)
  - *We will focus on the client delay for the enter operation.*
- **Synchronization delay**: the time interval between one process exiting the critical section and the next process entering it (when there is *only one* process waiting). Measures of the *throughput* of the system.

Analysis of Central Algorithm

- **Bandwidth**: the total number of messages sent in each *enter* and *exit* operation.
  - 2 messages for enter
  - 1 message for exit
- **Client delay**: the delay incurred by a process at each enter and exit operation (when *no* other process is in CS, or waiting)
  - 2 message latencies or 1 round-trip (request + grant) on enter.
- **Synchronization delay**: the time interval between one process exiting the critical section and the next process entering it (when there is *only one* process waiting)
  - 2 message latencies (release + grant)

Limitations of Central Algorithm

- The leader is the performance bottleneck and single point of failure.

Mutual exclusion in distributed systems

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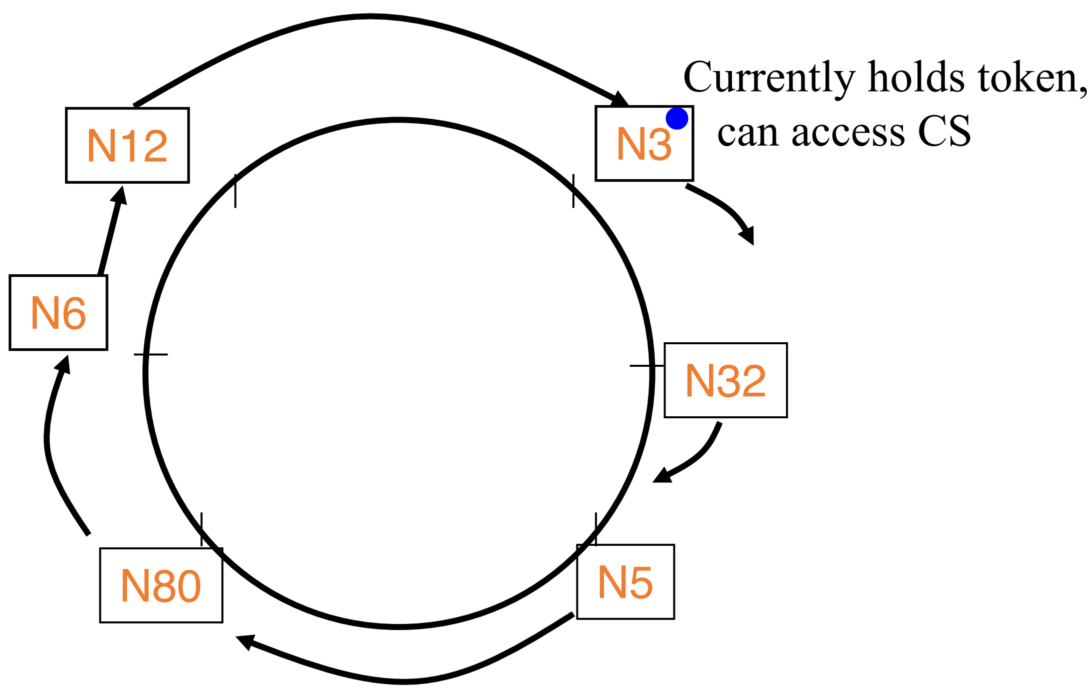
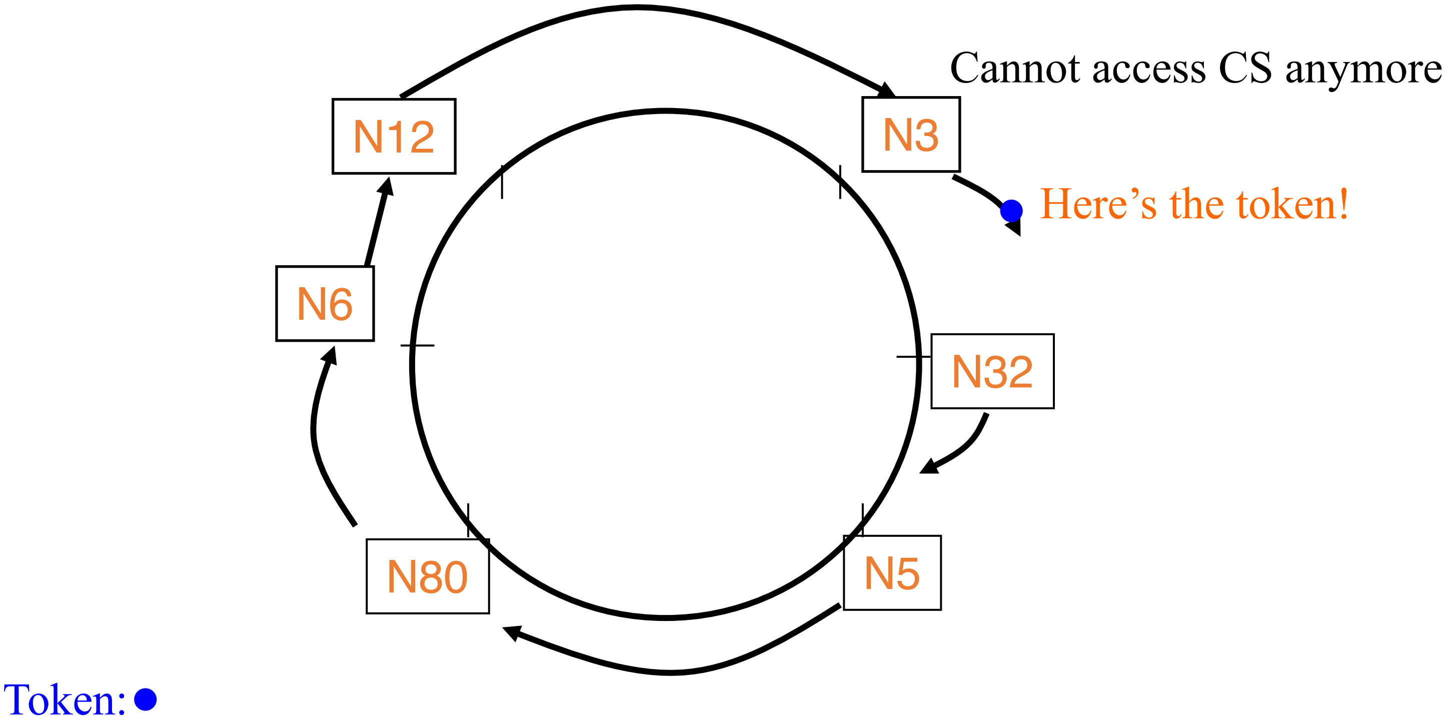
Ring-based Mutual Exclusion



Token: ●

Ring-based Mutual Exclusion



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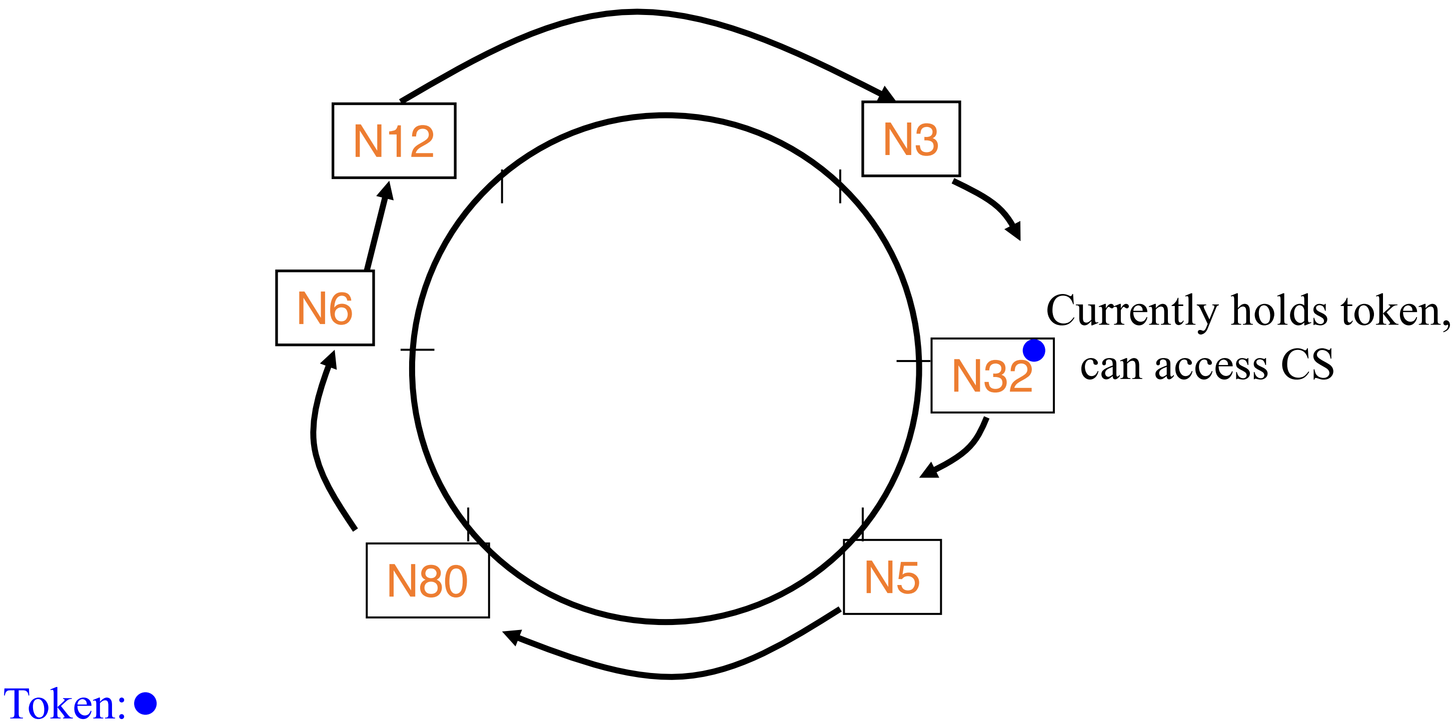

Ring-based Mutual Exclusion

- *N* Processes organized in a virtual ring
- Each process can send message to its successor in ring
- Exactly 1 token
- enter()
  - Wait until you get token
- exit() // already have token
  - Pass on token to ring successor
- If receive token, and not currently in enter(), just pass on token to ring successor

Analysis of Ring-based algorithm

- Safety
  - Exactly one token
- Liveness
  - Token eventually loops around ring and reaches requesting process (no failures)
- Ordering
  - Token not always obtained in order of enter events.

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Analysis of Ring-based algorithm

- Bandwidth
  - Per enter, 1 message at requesting process but up to *N* messages throughout system.
  - 1 message sent per exit.
  - *Constantly consumes bandwidth even when no process requires entry to the critical section (except when a process is executing critical section).*

Analysis of Ring-based algorithm

- Client delay:
  - Best case: just received token
  - Worst case: just sent token to neighbor
  - 0 to *N* message transmissions after entering enter()
- Synchronization delay between one process' exit() from the CS and the next process' enter():
  - Best case: process in enter() is successor of process in exit()
  - Worst case: process in enter() is predecessor of process in exit()
  - Between 1 and (*N-1*) message transmissions.
- *Can we improve upon this O(n) client and synchronization delays?*
  - *Next class!*