Distributed Systems

CS425/ECE428

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Acknowledgements for some of materials: Indy Gupta and Nikita Borisov

Logistics

- MP1 has been released.
  - Due on March 4th, 11:59pm.
- HW1 is due next week Monday.
  - You should be able to solve all questions by now (except 7c).
  - You should be able to solve 7c after the end of today's class.
- Academic Integrity:
  - Violation: copying from peers, from previous years', from the web, etc.

Today's agenda

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

Recap: Multicast

- Useful communication mode in distributed systems:
  - Writing an object across replica servers.
  - Group messaging.
  - …..
- Basic multicast (B-multicast): unicast send to each process in the group.
  - Does not guarantee consistent message delivery if sender fails.
- Reliable multicast (R-mulicast):
  - Defined by three properties: *integrity, validity, agreement*.
  - If some correct process multicasts a message **m**, then all other correct processes deliver **m** (exactly once).
  - When a process receives a message 'm' for the first time, it re-multicasts it again to other processes in the group.

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*.

Ordered Multicast

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Implementing total order multicast

- Basic idea:
  - Same sequence number counter across different processes.
  - Instead of different sequence number counter for each process.

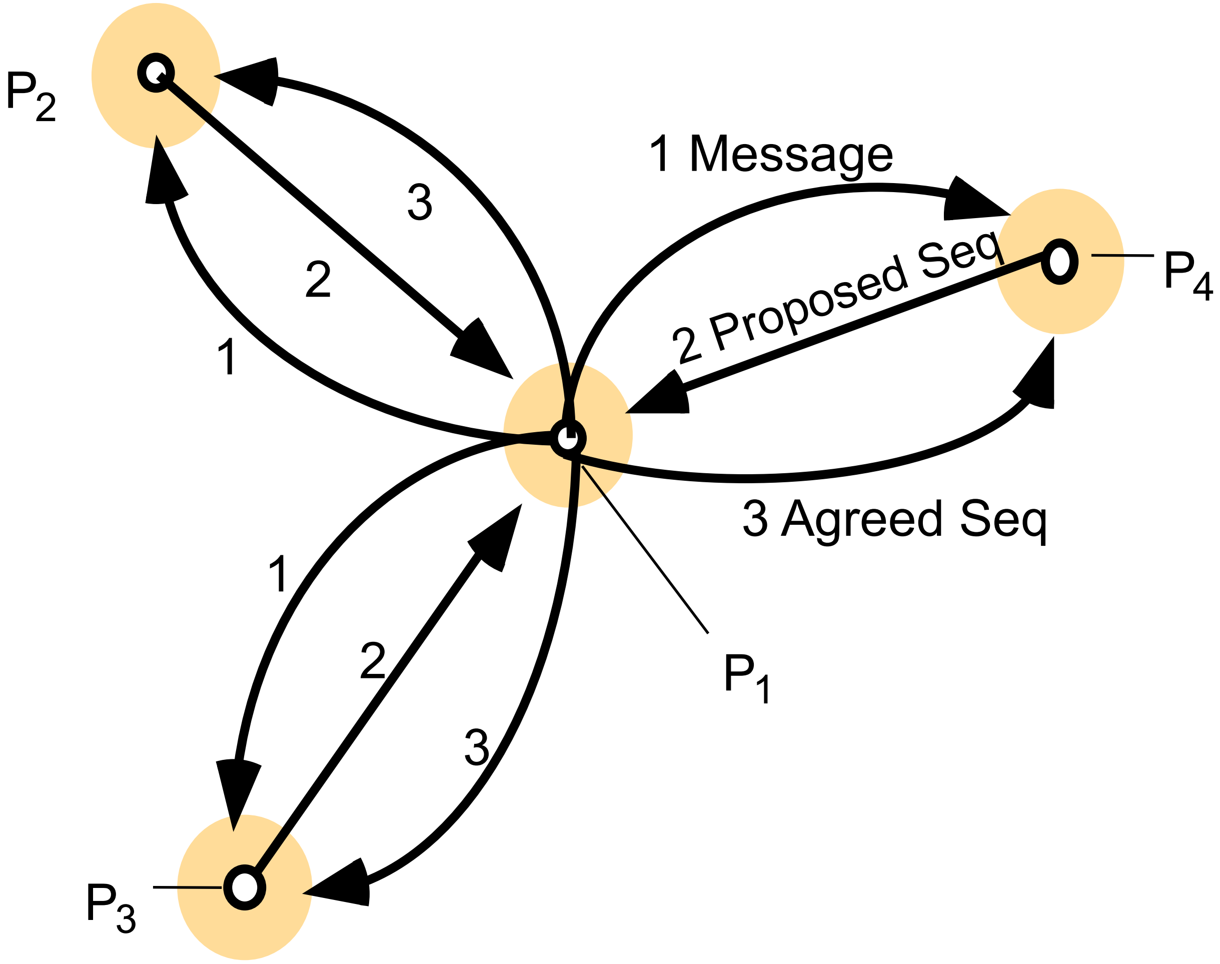
- Two types of approach
  - Using a centralized sequencer
  - A decentralized mechanism (ISIS)

Implementing total order multicast

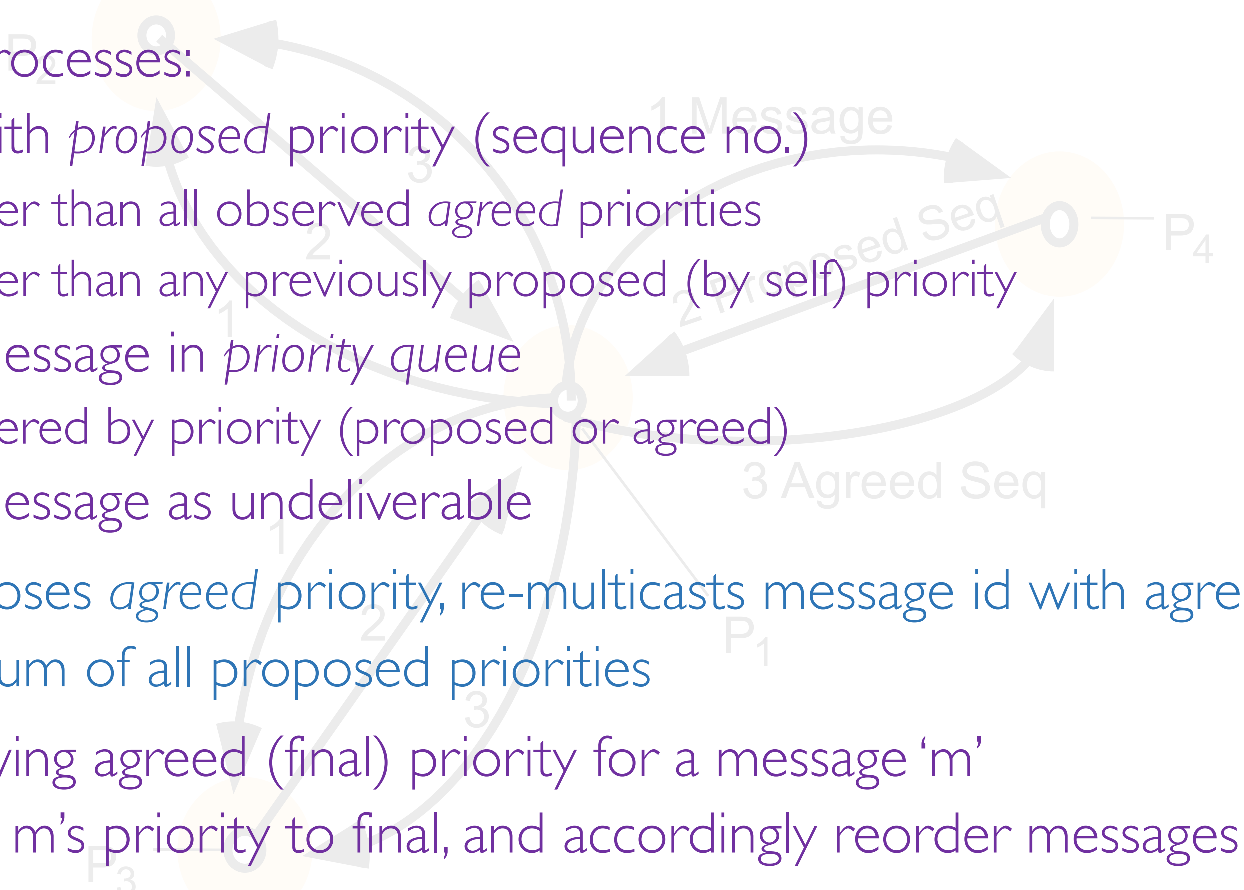
- Basic idea:
    - Same sequence number counter across different processes.
    - Instead of different sequence number counter for each process.

- Two types of approach
    - Using a centralized sequencer
    - **A decentralized mechanism (ISIS)**

ISIS algorithm for total ordering

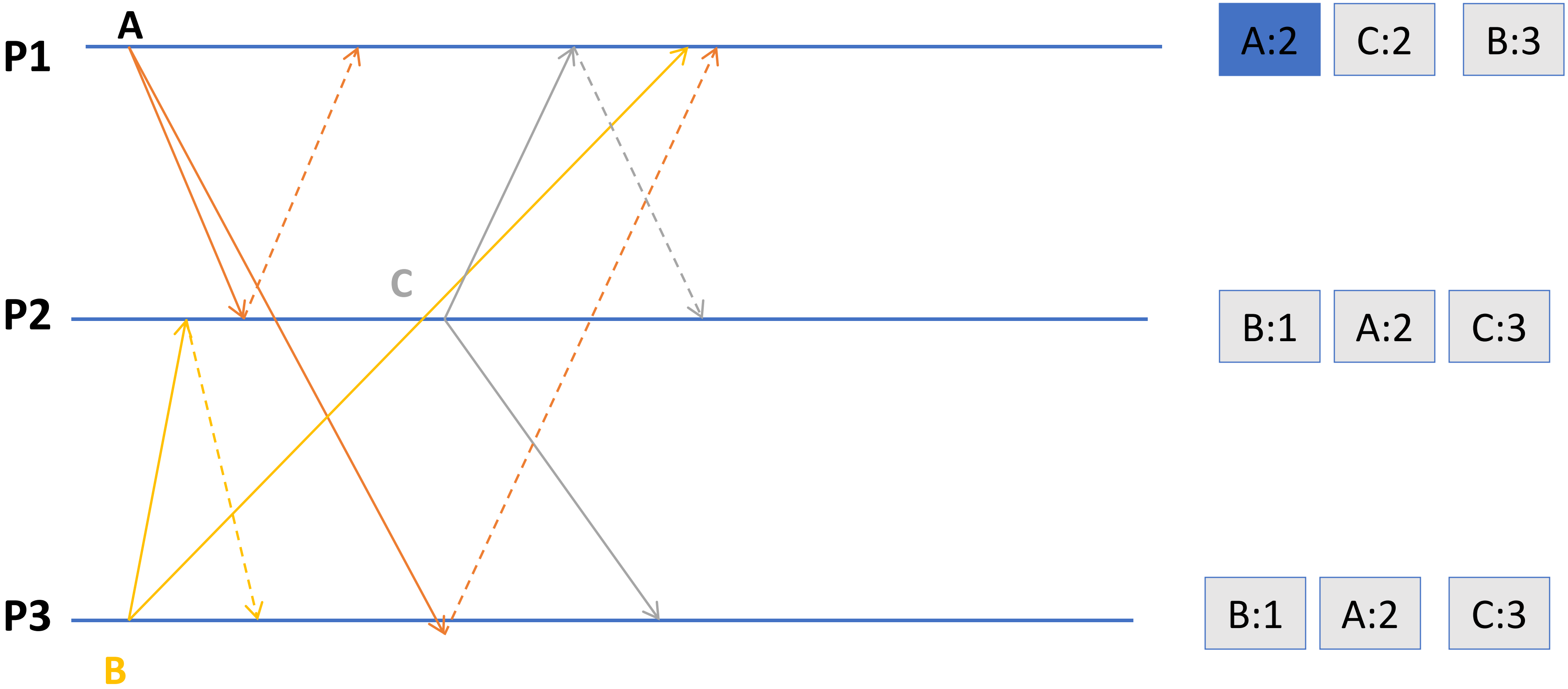


ISIS algorithm for total ordering



- Sender multicasts message to everyone.
- Receiving processes:
  - reply with *proposed* priority (sequence no.)
    - larger than all observed *agreed* priorities
    - larger than any previously proposed (by self) priority
  - store message in *priority queue*
    - ordered by priority (proposed or agreed)
  - mark message as undeliverable
- Sender chooses *agreed* priority, re-multicasts message id with agreed priority
  - maximum of all proposed priorities
- Upon receiving agreed (final) priority for a message 'm'
  - Update m's priority to final, and accordingly reorder messages in queue.
  - mark the message m as deliverable.
  - deliver any deliverable messages at front of priority queue.

Example: ISIS algorithm



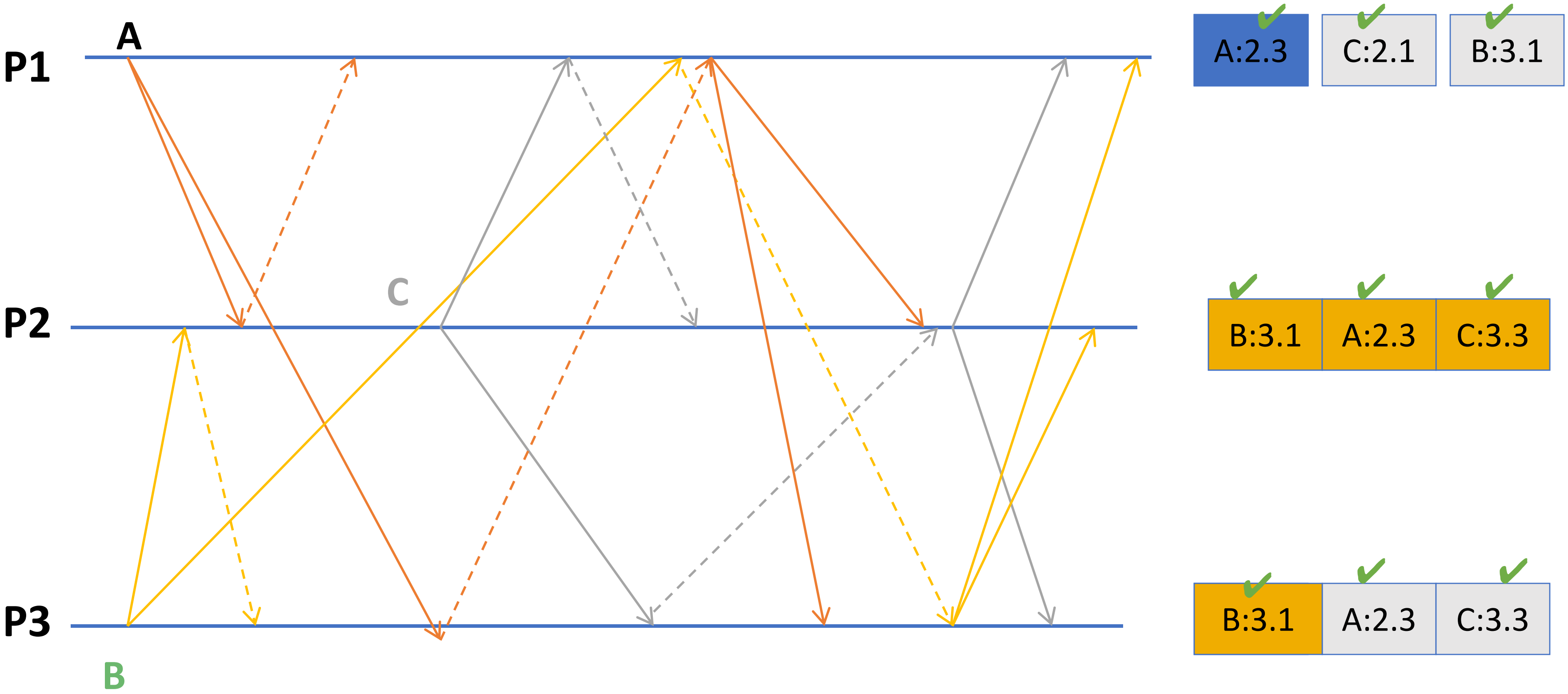
How do we break ties?

- Problem: priority queue requires unique priorities.

- Solution: add process # to suggested priority.
  - priority.(*id of the process that proposed the priority*)
  - i.e., 3.2 == process 2 proposed priority 3

- Compare on priority first, use process # to break ties.
  - 2.1 > 1.3
  - 3.2 > 3.1

Example: ISIS algorithm



[see .pptx file for animations]

Proof of total order with ISIS

- Consider two messages, m_1 and m_2, and two processes, p and p'.
- Suppose that p delivers m_1 before m_2.
- When *p* delivers m_1, it is at the head of the queue. m_2 is either:
  - Already in *p*'s queue, and deliverable, so
    - $\text{finalpriority}(m_1) < \text{finalpriority}(m_2)$
  - Already in *p*'s queue, and not deliverable, so
    - $\text{finalpriority}(m_1) < \text{proposedpriority}(m_2) <= \text{finalpriority}(m_2)$
  - Not yet in *p*'s queue:
    - same as above, since proposed priority > priority of any delivered message
- Suppose *p*' delivers m_2 before m_1, by the same argument:
  - $\text{finalpriority}(m_2) < \text{finalpriority}(m_1)$
  - Contradiction!

Ordered Multicast

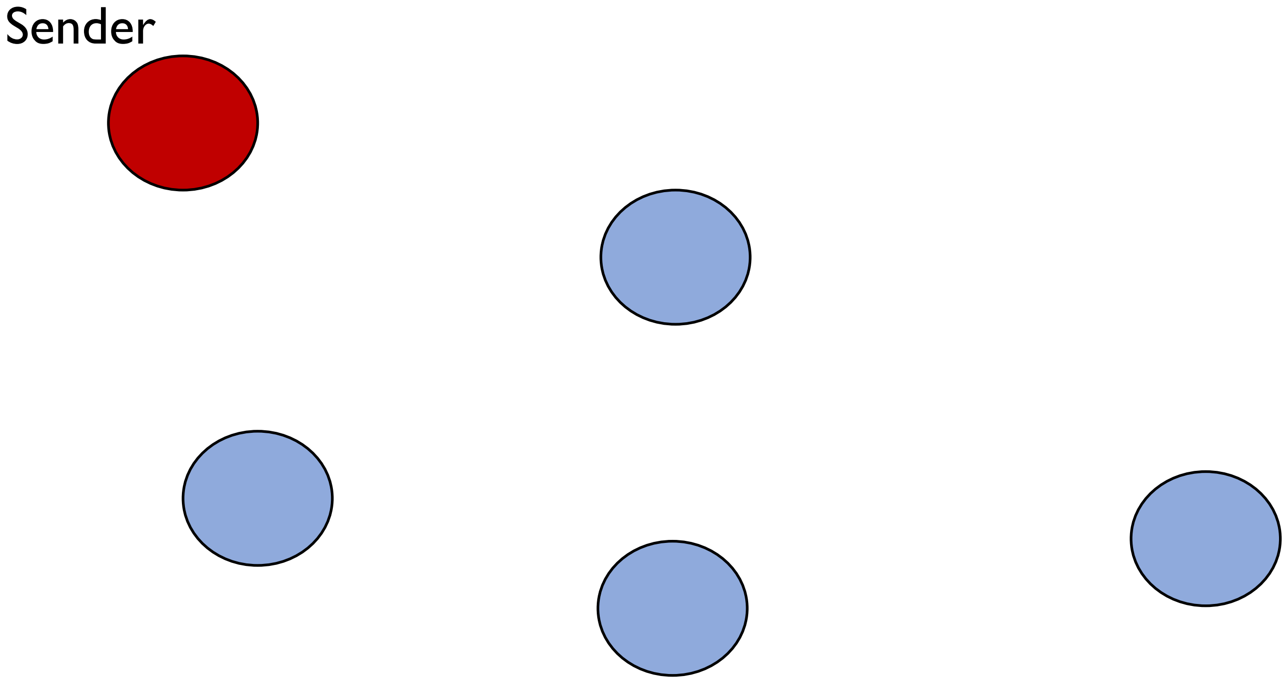
- FIFO ordering
  - If a correct process issues multicast(*g*,*m*) and then multicast(*g*,*m'*), then every correct process that delivers *m'* will have already delivered m.
- Causal ordering
  - If multicast(*g*,*m*) → multicast(*g*,*m'*) then any correct process that delivers *m'* will have already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

More efficient multicast mechanisms

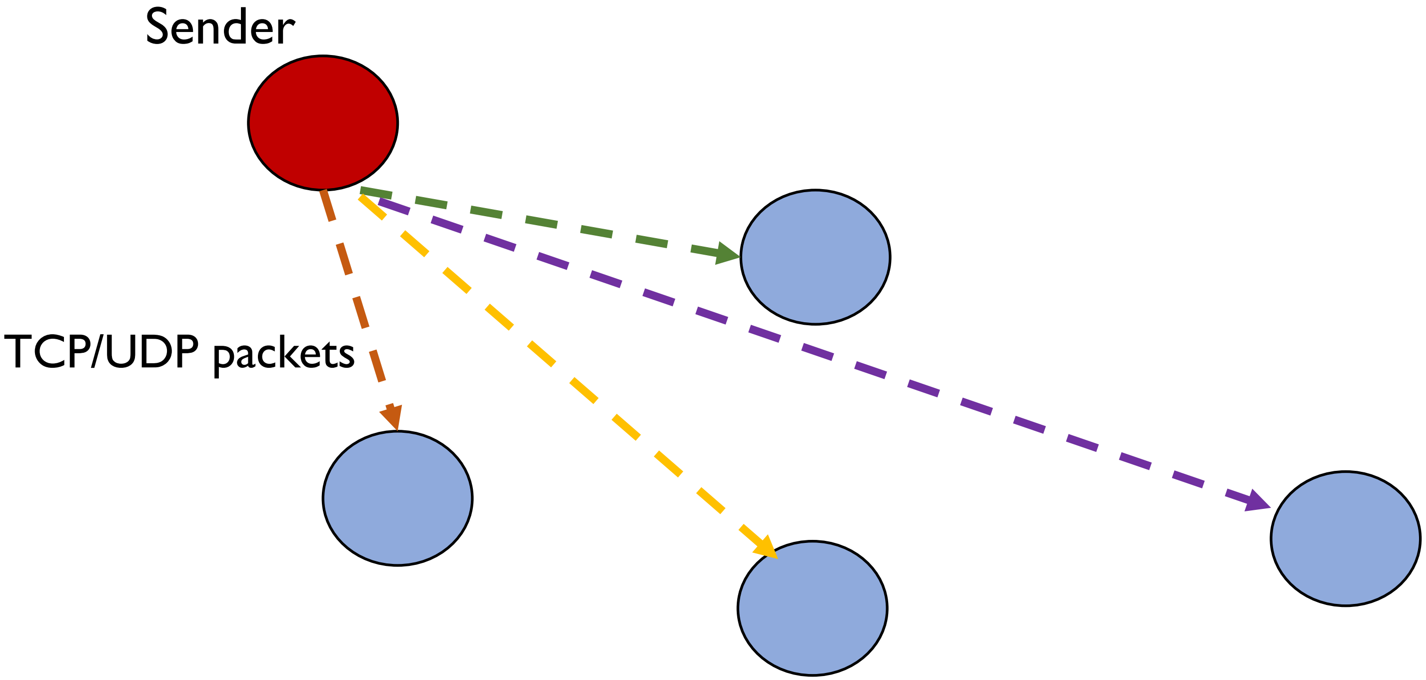
- Our focus so far has been on the application-level semantics of multicast.

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

B-Multicast



B-Multicast using unicast sends



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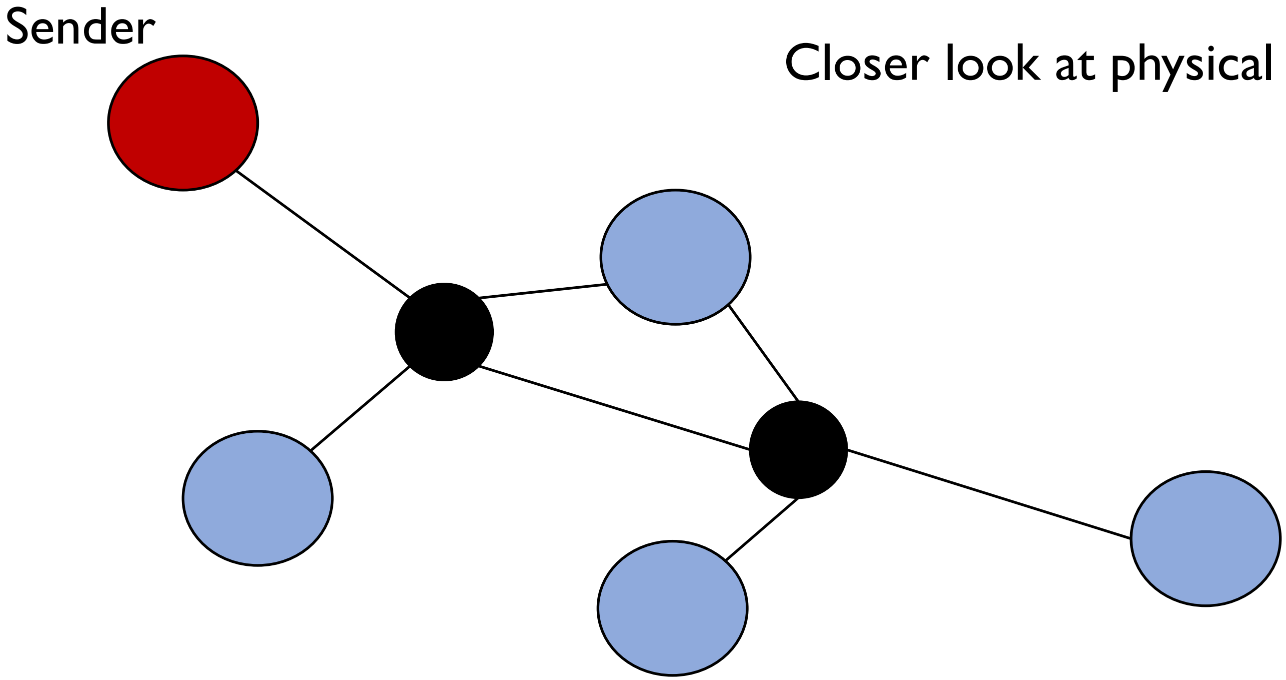
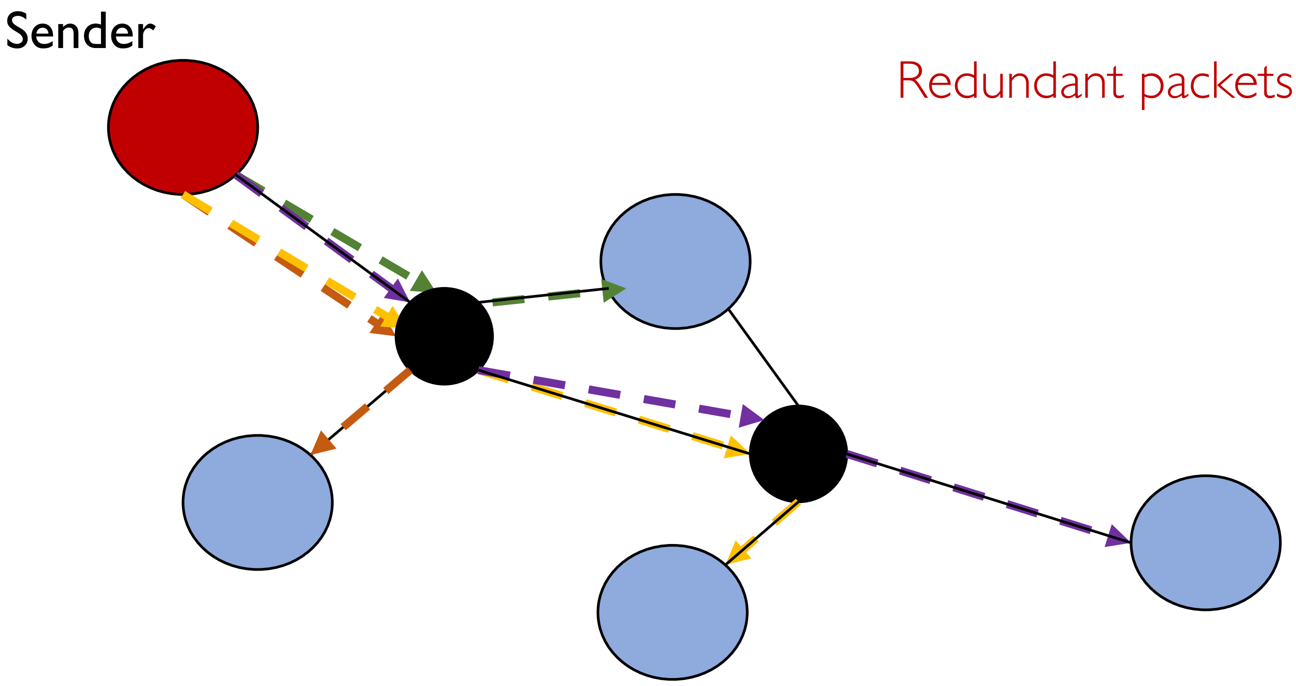


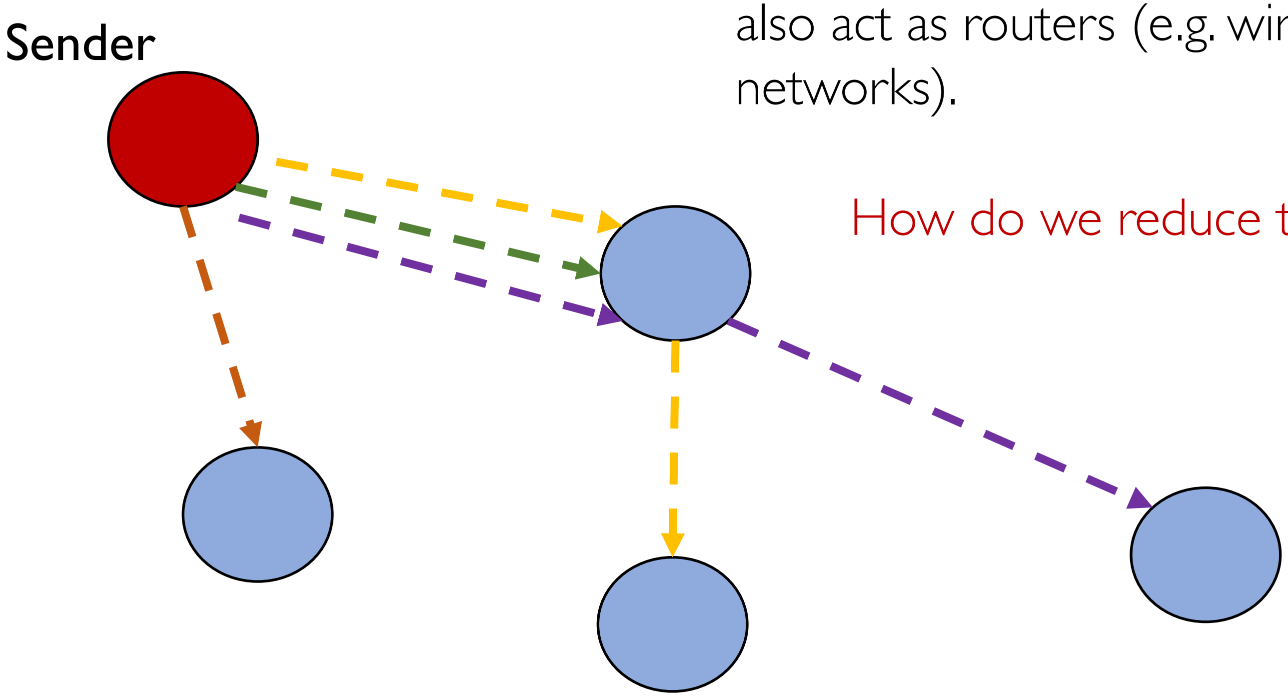
Closer look at physical network paths.

B-Multicast using unicast sends



Redundant packets!

B-Multicast using unicast sends

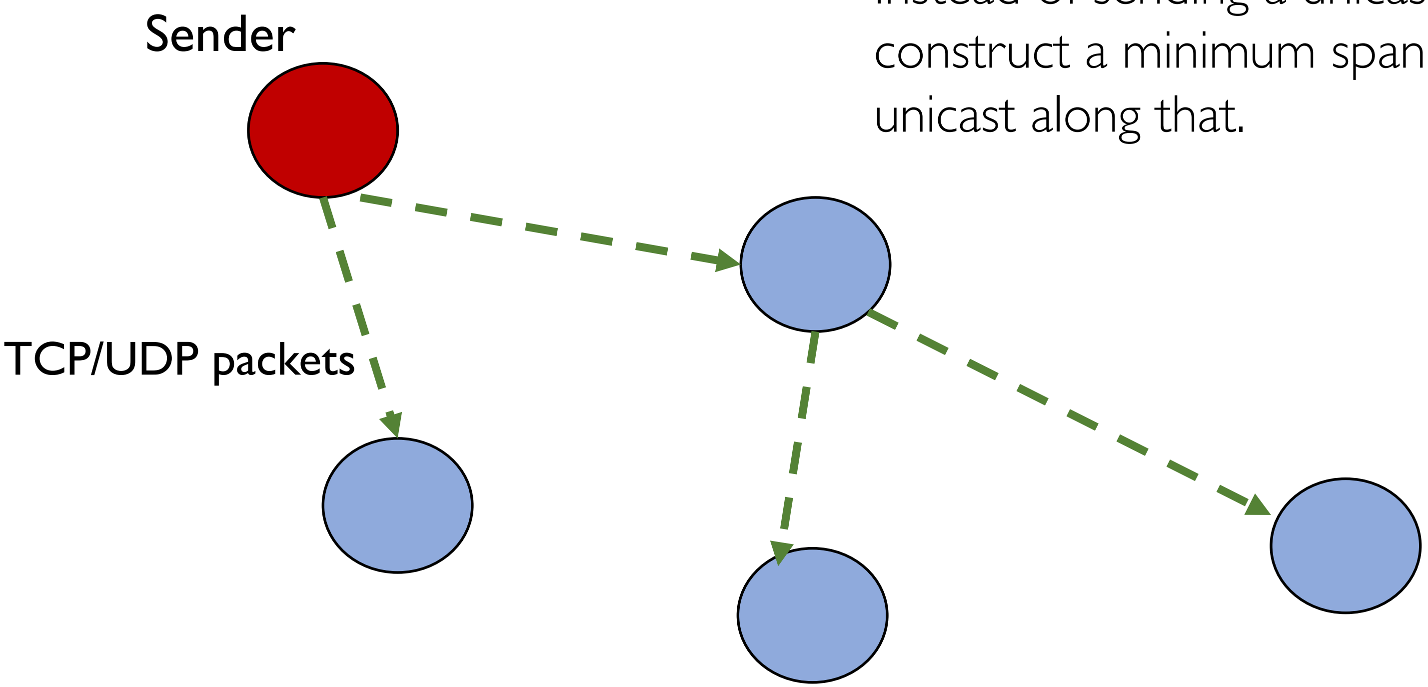


Similar redundancy when individual nodes also act as routers (e.g. wireless sensor networks).

How do we reduce the overhead?

Tree-based multicast

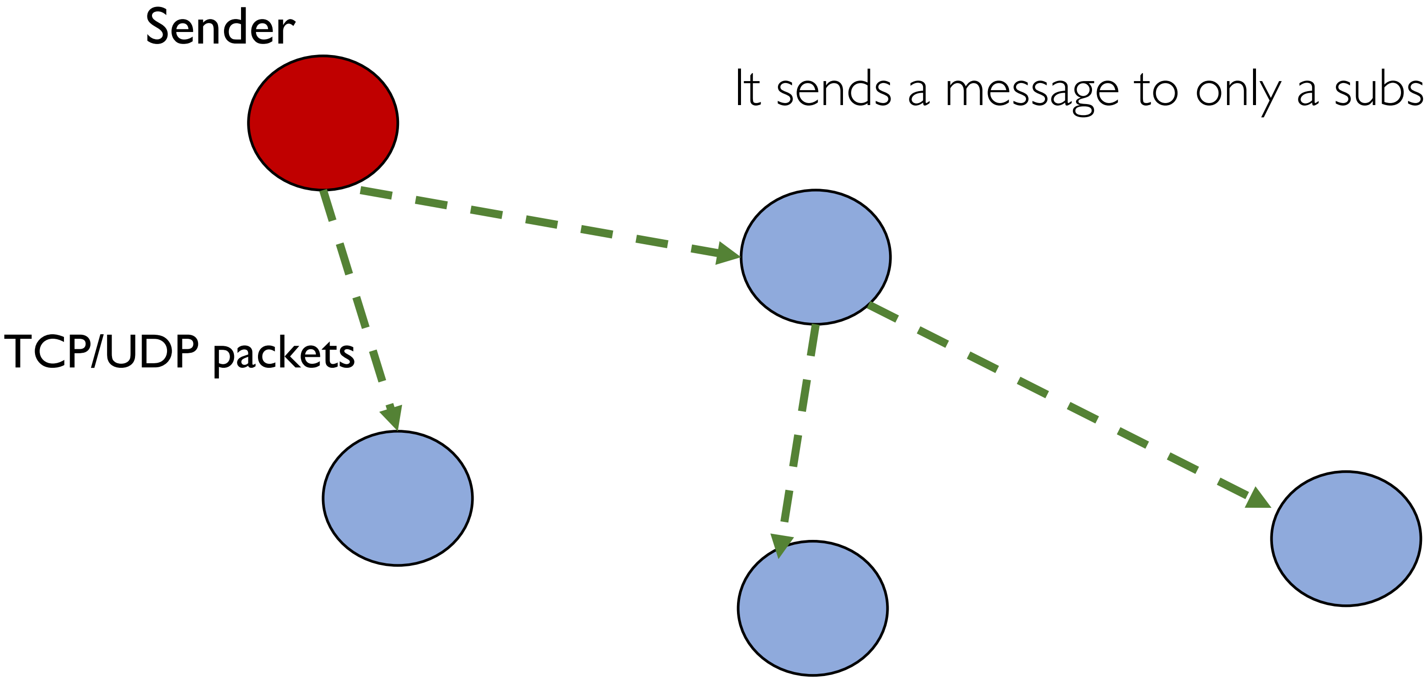
Instead of sending a unicast to all nodes, construct a minimum spanning tree and unicast along that.



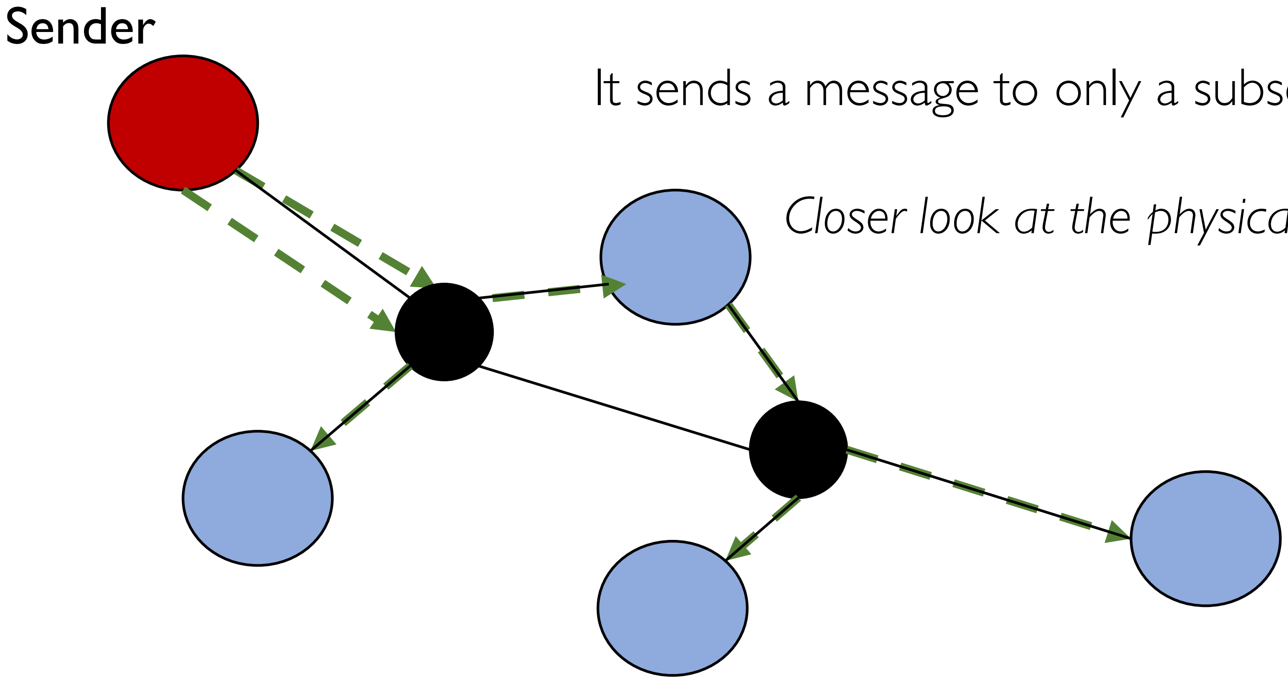
Tree-based multicast

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

It sends a message to only a subset of processes.



Tree-based multicast

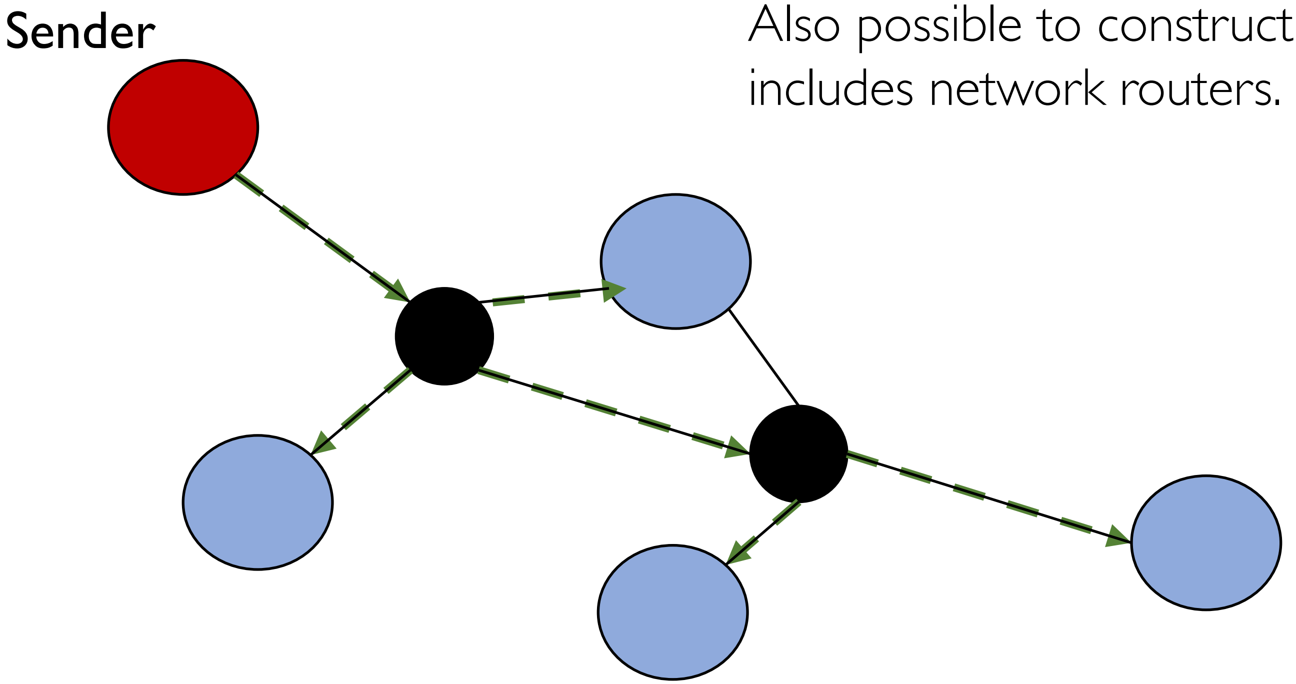


A process does not directly send messages to *all* other processes in the group.

It sends a message to only a subset of processes.

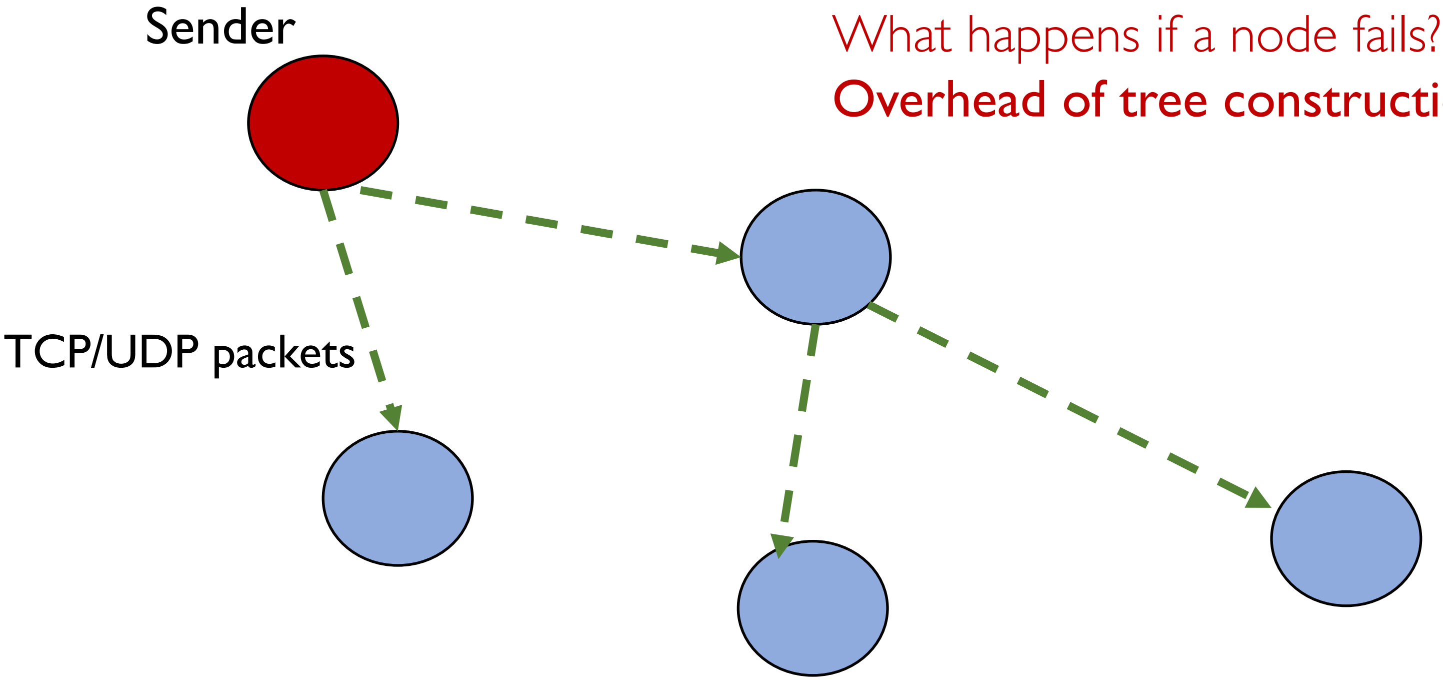
Closer look at the physical network.

Tree-based multicast



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

Tree-based multicast

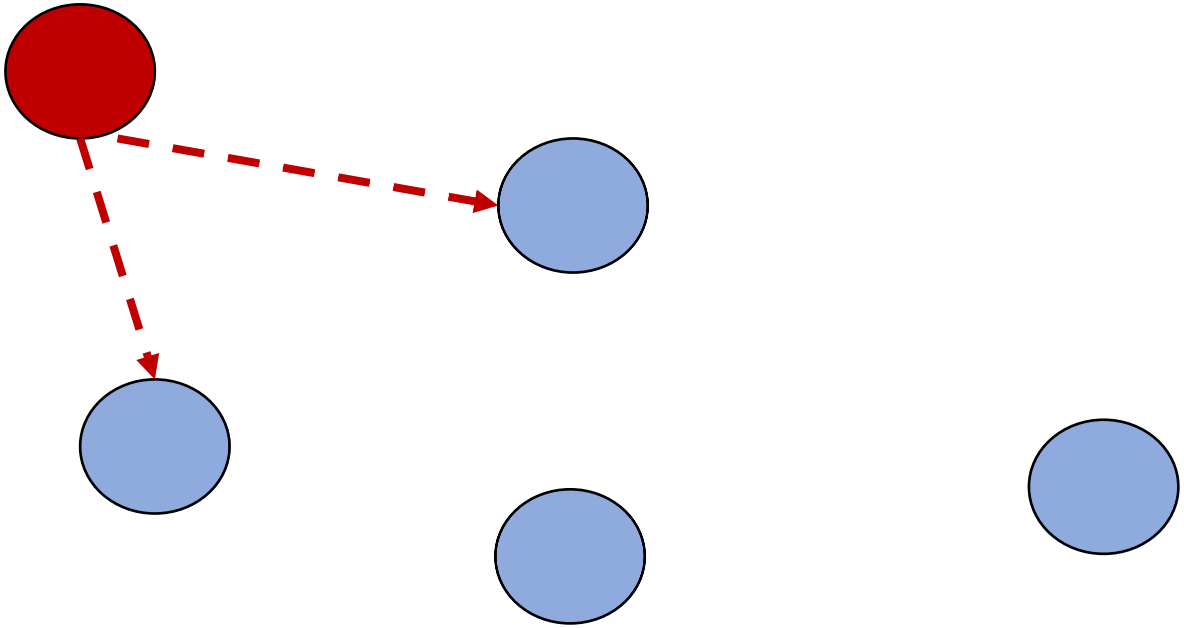


What happens if a node fails?

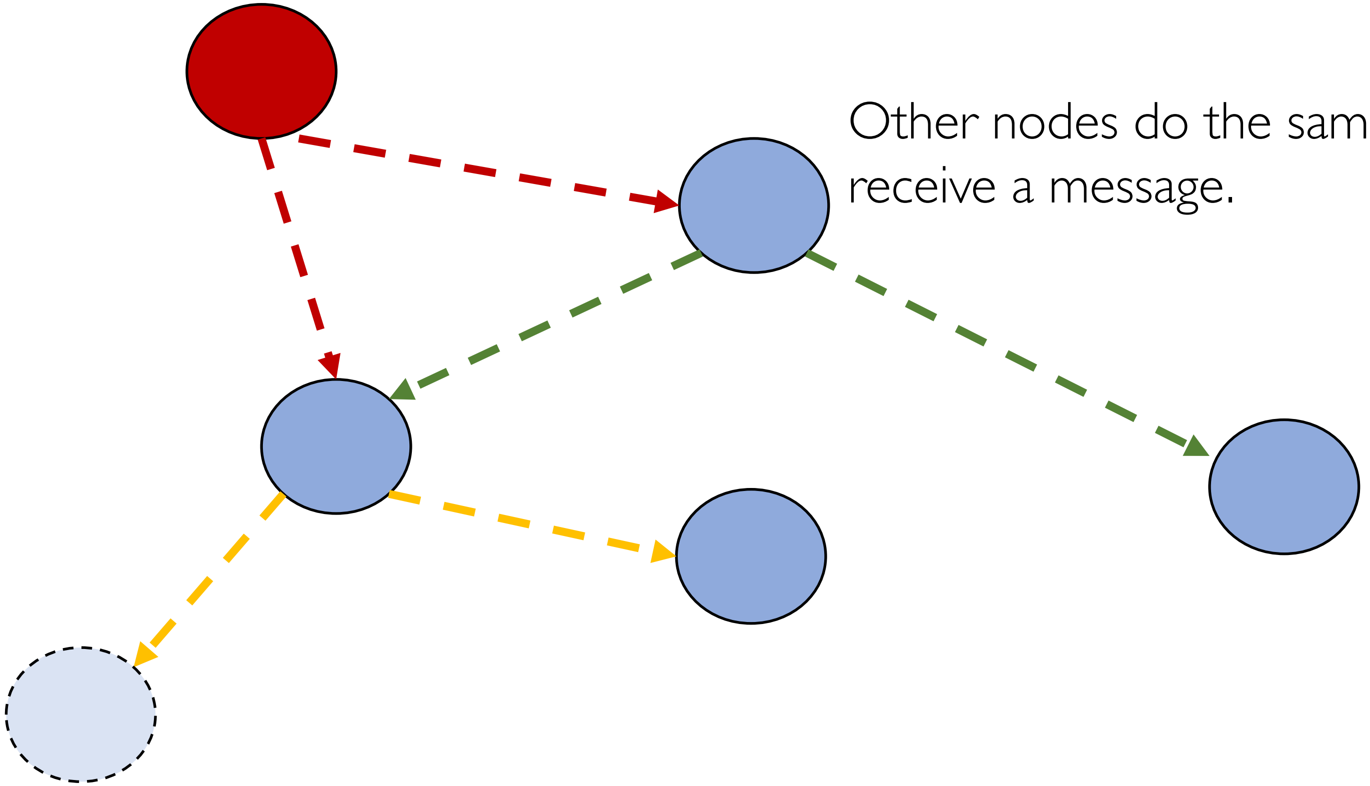
Overhead of tree construction and repair.

Third approach: Gossip

Transmit to b random targets.



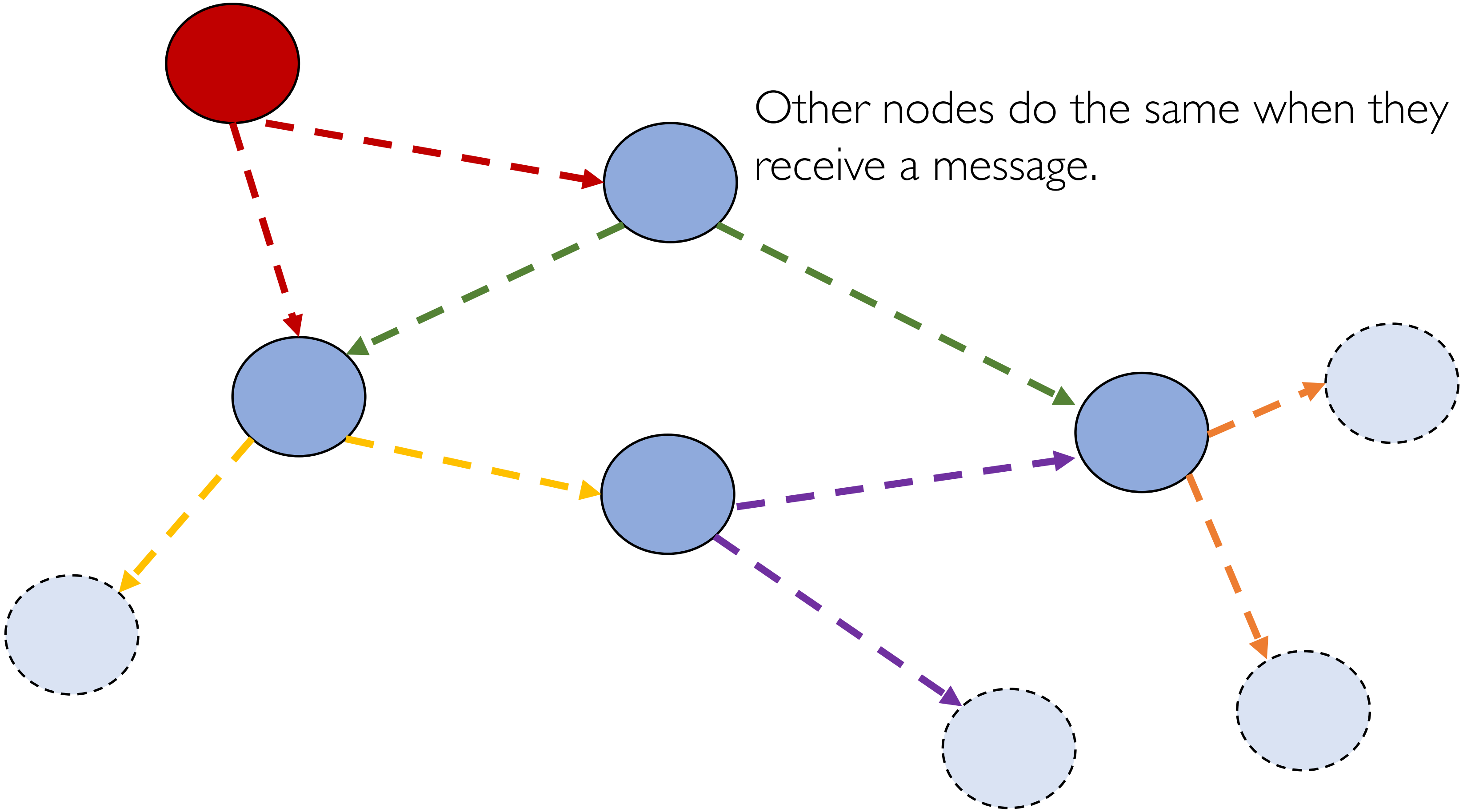
Third approach: Gossip



Transmit to b random targets.

Other nodes do the same when they receive a message.

Third approach: Gossip



Transmit to b random targets.

Other nodes do the same when they receive a message.

Third approach: Gossip

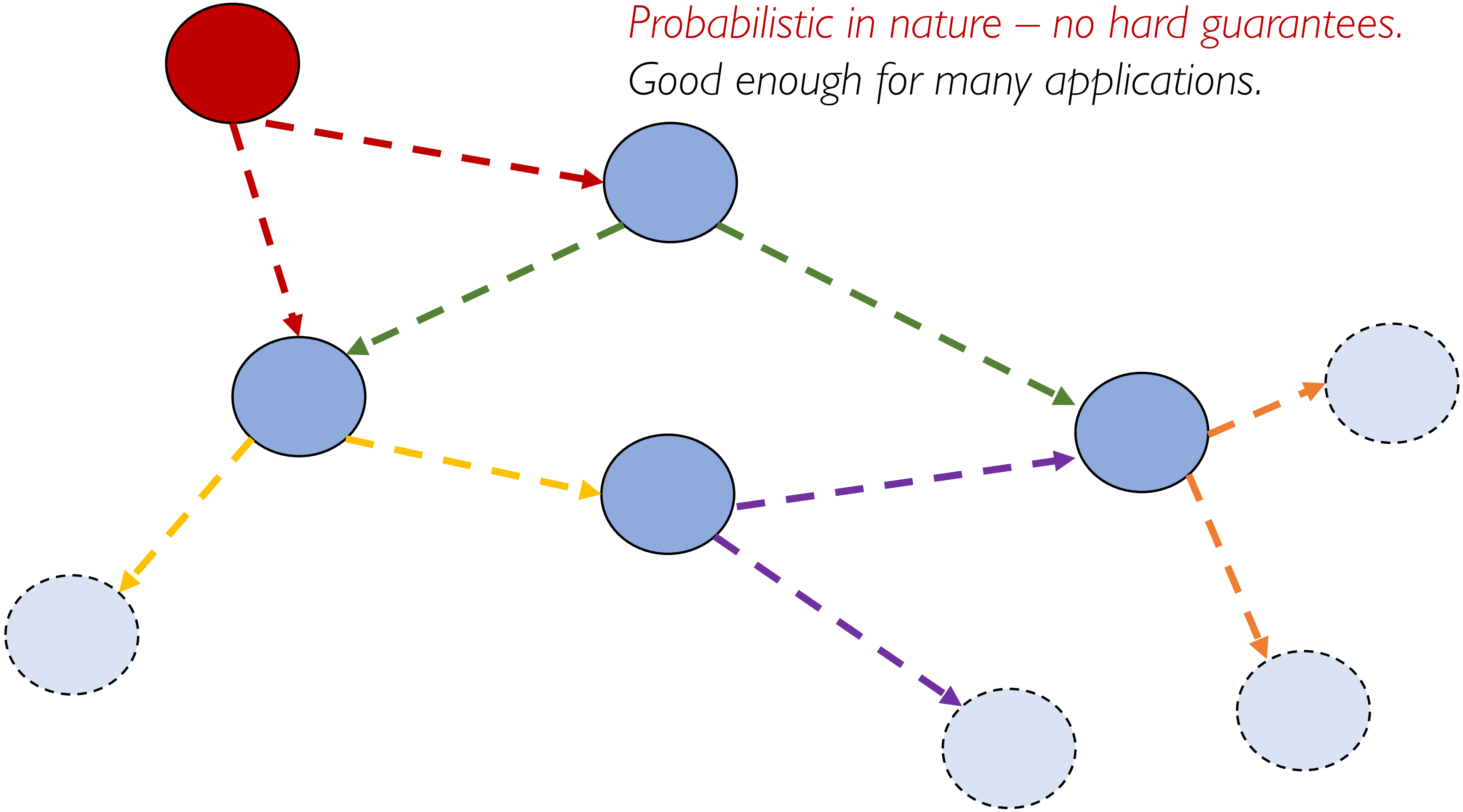
No "tree-construction" overhead.

More efficient than unicasting to all receivers.

Also known as "epidemic multicast".

Probabilistic in nature – no hard guarantees.

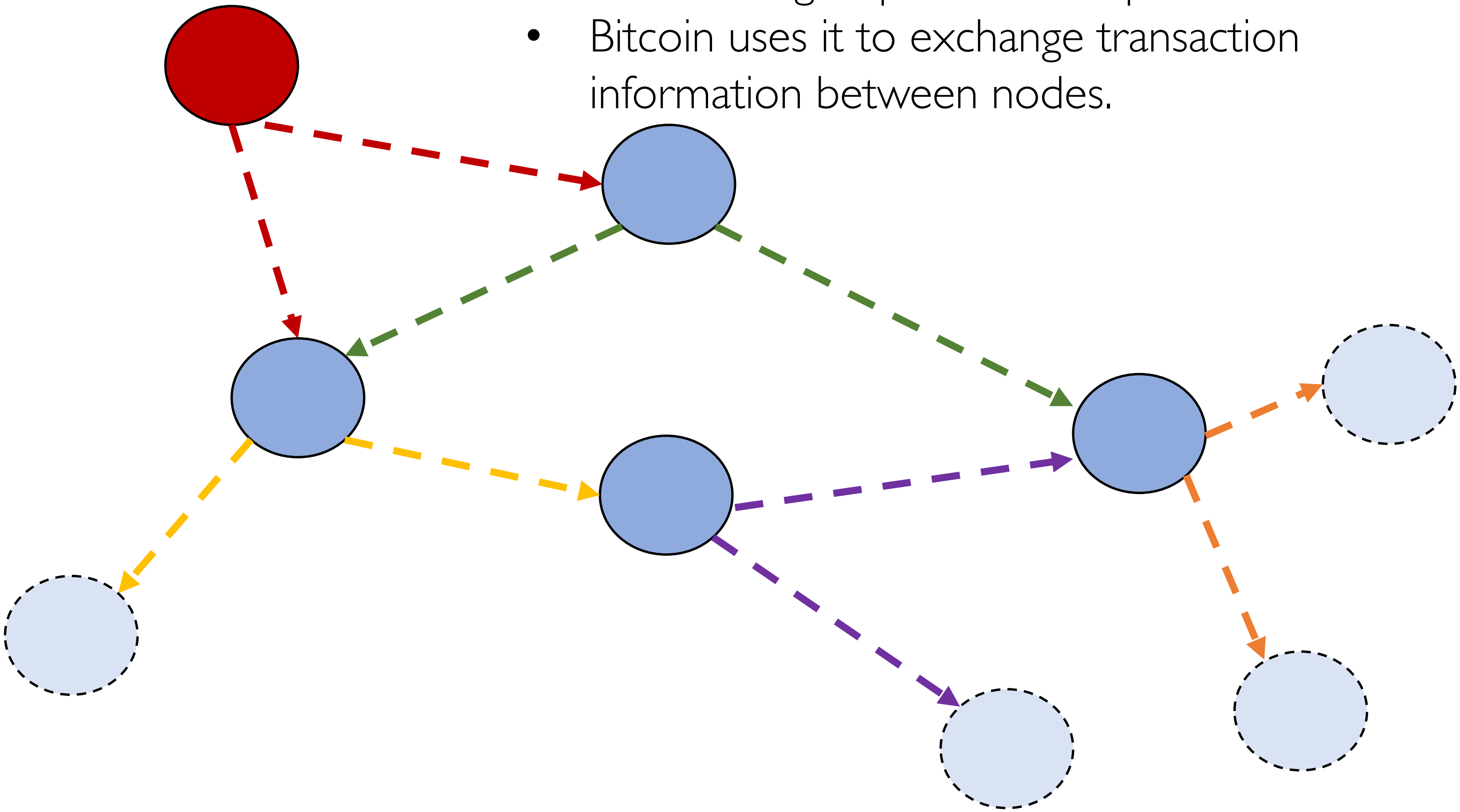
Good enough for many applications.



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?

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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 at most one process 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()
    obtain bank amount;
    add in deposit;
    update bank amount;
      // AccessResource() end
    exit();
```

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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 Pi
else
    Add Pi to queue
```

  - On receiving a token from process P*i*

```
if (queue is not empty)
    Dequeue head of queue (say Pj), 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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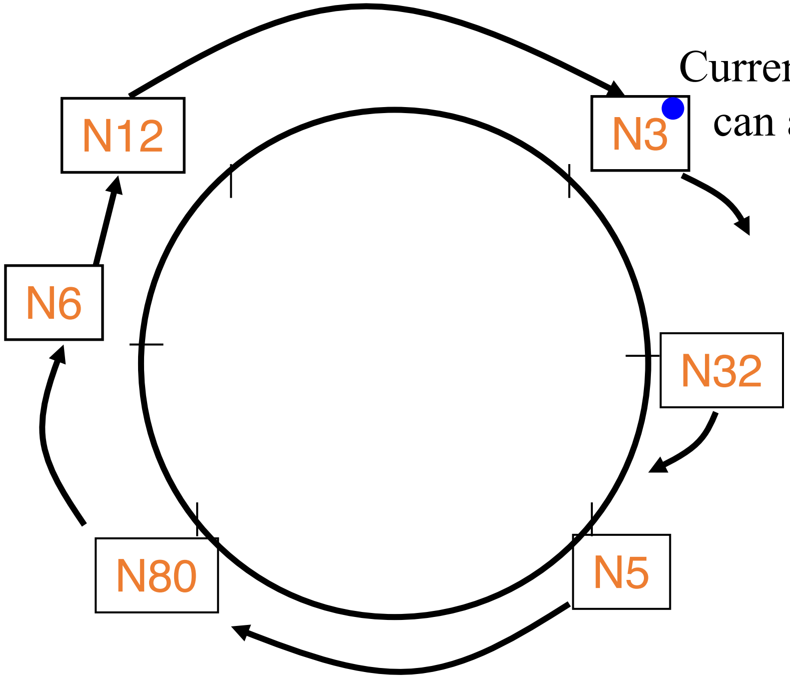
  - Central server algorithm
  - Ring-based algorithm
  - Ricart-Agrawala Algorithm
  - Maekawa Algorithm

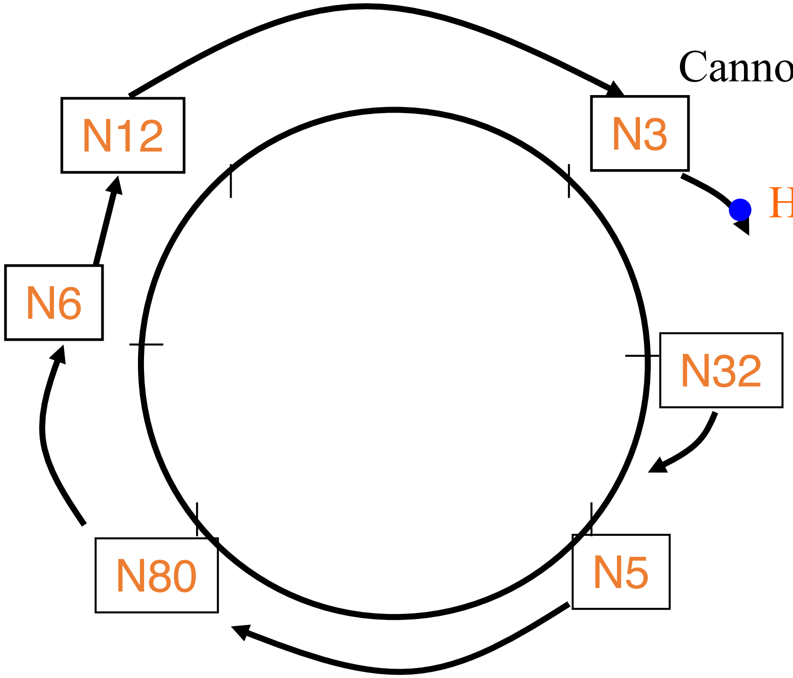
Ring-based Mutual Exclusion



Currently holds token, can access CS

Token: ●

Ring-based Mutual Exclusion

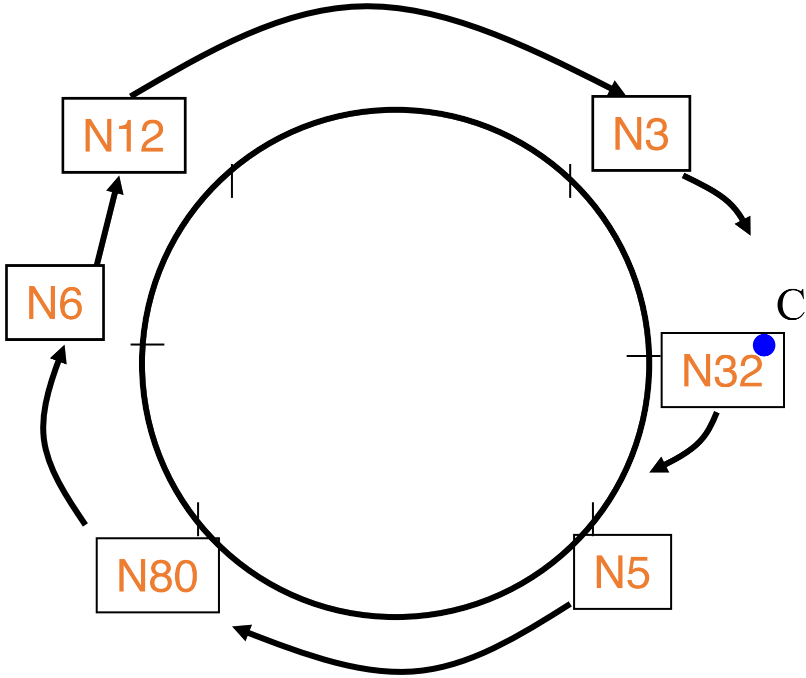


Cannot access CS anymore

Here's the token!

Token: ●

Ring-based Mutual Exclusion



Currently holds token, can access CS

Token: ●

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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- Safety
  - Exactly one token
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- Ordering
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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?*

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 (next class)
  - Maekawa Algorithm

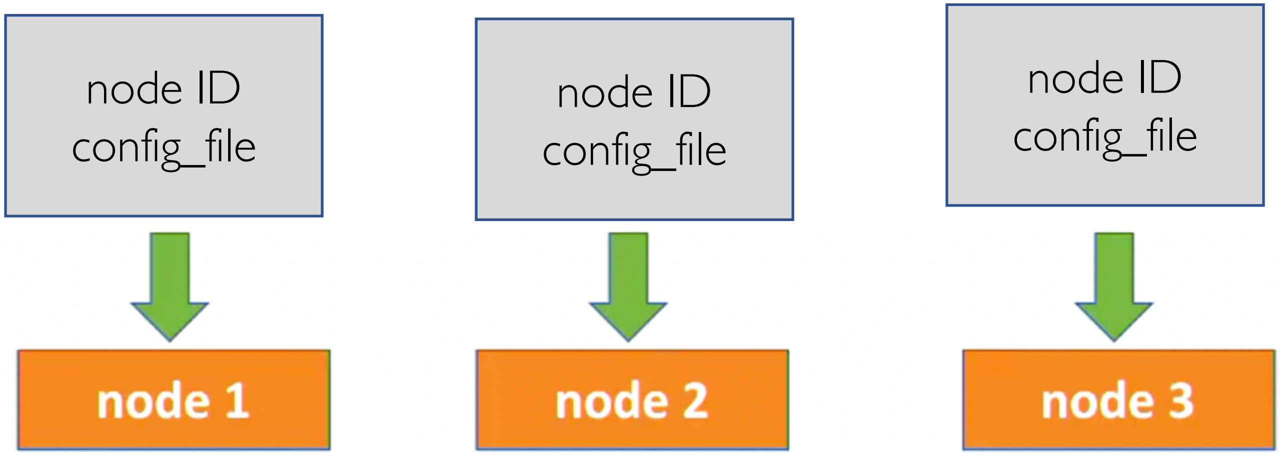
MP1: Event Ordering

- https://courses.grainger.illinois.edu/ece428/sp2024/mps/mp1.html
- Lead TA: Siddharth Lal

- Task:
  - Collect **transaction** events on distributed **nodes**.
  - **Multicast** transactions to all nodes while maintaining **total order**.
  - Ensure transaction **validity**.
  - Handle **failure** of arbitrary nodes.

- Objective:
  - Build a decentralized multicast protocol to ensure total ordering and handle node failures.

MP1 Architecture Setup



node ID
config_file

node 1

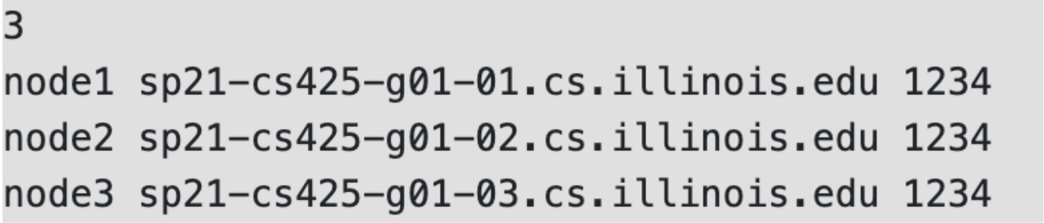
node ID
config_file

node 2

node ID
config_file

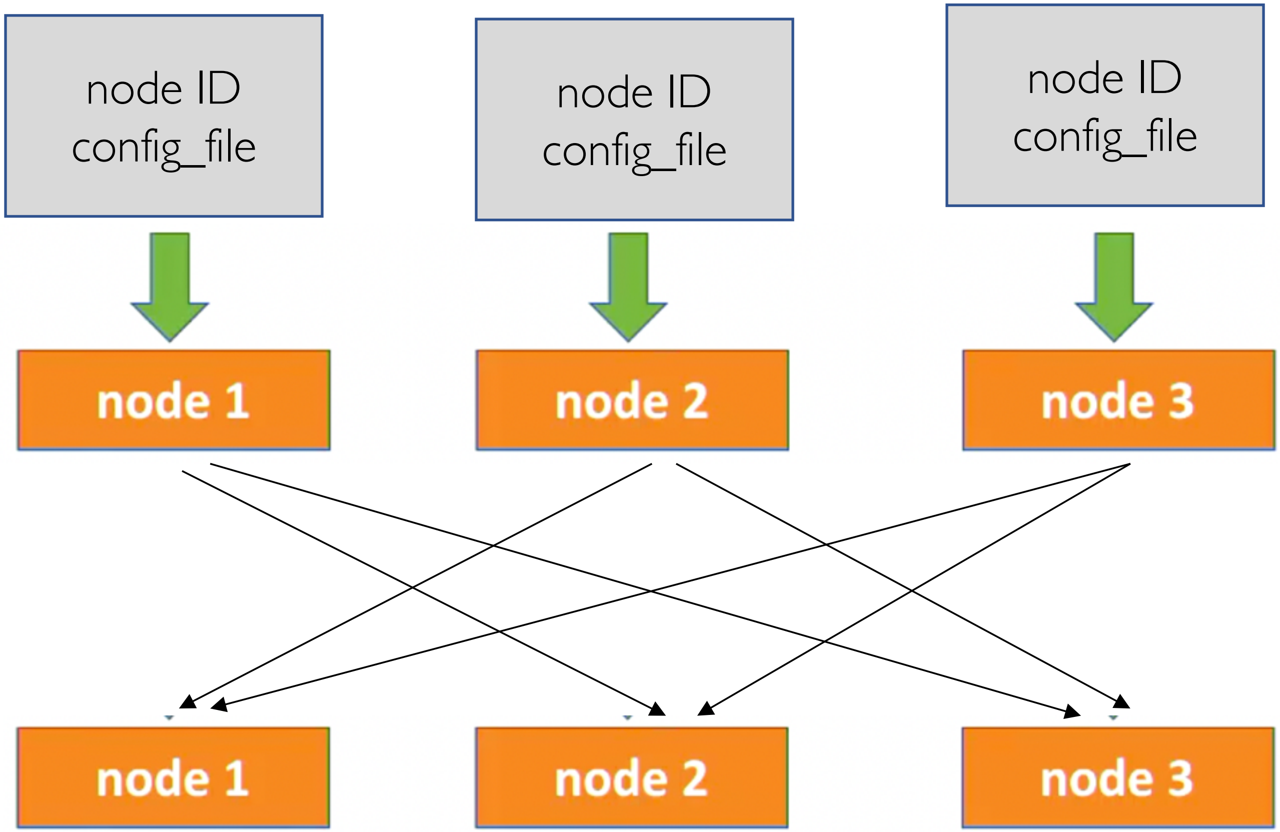
node 3

- Example input arguments for first node:
  `./mp1_node node1 config.txt`
- config.txt looks like this:



```
3
node1 sp21-cs425-g01-01.cs.illinois.edu 1234
node2 sp21-cs425-g01-02.cs.illinois.edu 1234
node3 sp21-cs425-g01-03.cs.illinois.edu 1234
```

MPI Architecture Setup



node ID
config_file

node ID
config_file

node ID
config_file

node 1

node 2

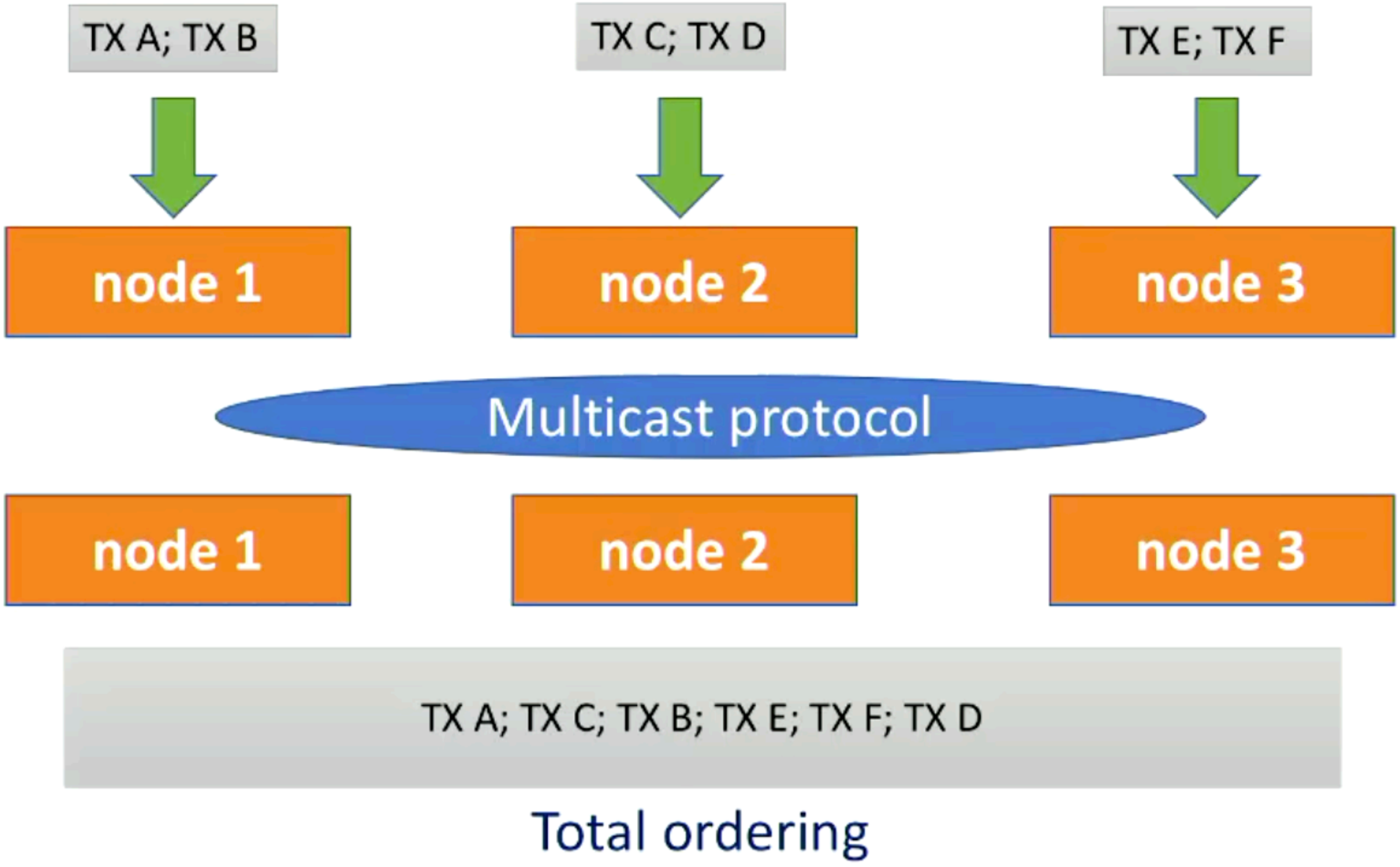
node 3

node 1

node 2

node 3

MPI Architecture



TX A; TX B

TX C; TX D

TX E; TX F

node 1

node 2

node 3

Multicast protocol

node 1

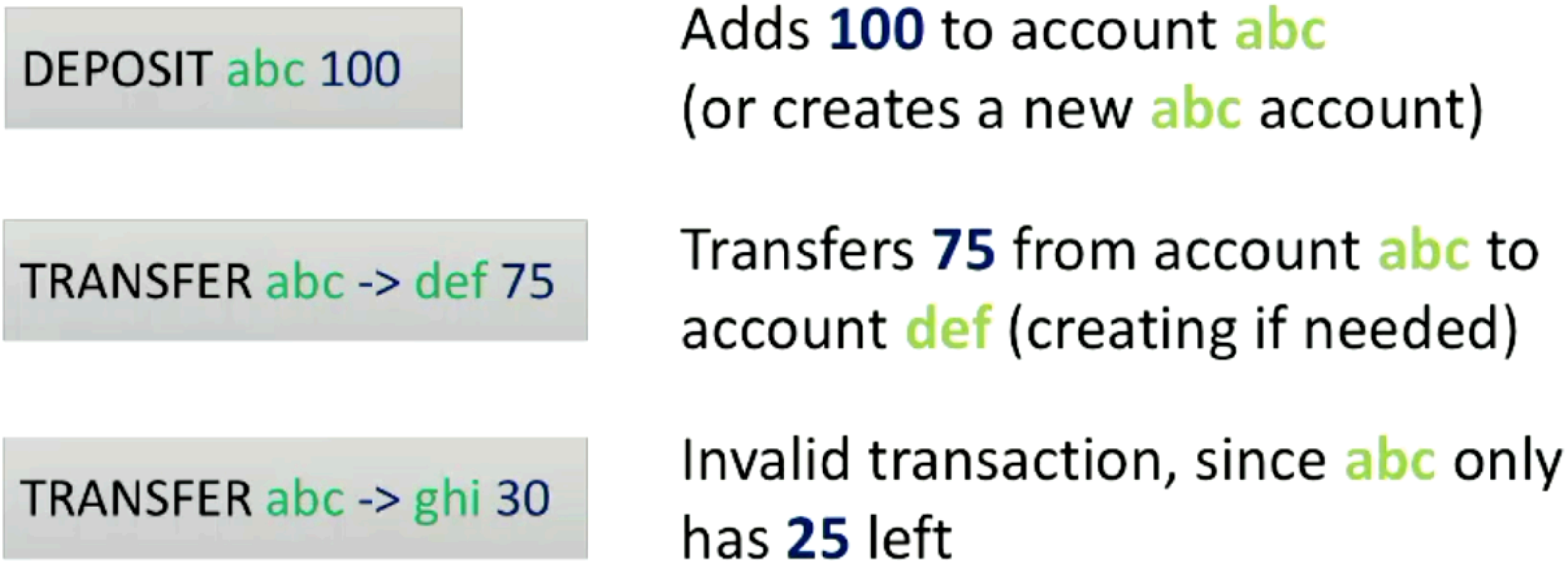
node 2

node 3

TX A; TX C; TX B; TX E; TX F; TX D

Total ordering

Transaction Validity



DEPOSIT abc 100	Adds **100** to account abc (or creates a new abc account)
TRANSFER abc -> def 75	Transfers **75** from account abc to account def (creating if needed)
TRANSFER abc -> ghi 30	Invalid transaction, since abc only has **25** left

Transaction Validity: ordering matters

DEPOSIT xyz 50
TRANSFER xyz -> wqr 40
TRANSFER xyz -> hjk 30
[invalid TX]

BALANCES xyz:10 wqr:40

DEPOSIT xyz 50
TRANSFER xyz -> hjk 30
TRANSFER xyz -> wqr 40
[invalid TX]

BALANCES xyz:20 hjk:30

Graph

- Compute the "processing time" for each transaction:
  - Time difference between when it was generated (read) at a node, and when it was **processed** by the last (alive) node.

- Plot the CDF (cumulative distribution function) of the transaction processing time for each evaluation scenario.

MP1: Logistics

- Due on March 4th.
  - Late policy: Can use part of your 168hours of grace period accounted per student over the entire semester.
- You are allowed to reuse code from MP0.
  - Note: MP1 requires all nodes to connect to each other, as opposed to each node connecting to a central logger.
- Read the specification carefully. Start early!!