CS60002:
Distributed Systems

Spring 2021

Basic Information

- Course webpage: cse.iitkgp.ac.in/~agupta/distsys
- Goal of the course: Introduce you to distributed system design
  - Will cover both algorithms and system design issues
  - You should be able to
    - Design at least a simple distributed system
    - Explain (at least to some depth) the working of some of the distributed systems you see around you
- Evaluation: Assignments, tests, term papers, project
  - Details will be notified later

What is a Distributed System?

"A distributed system is a system where I can't get my work done because a computer has failed that I've never even heard of."

- Leslie Lamport

What is a Distributed System?

A network of autonomous machines/devices that communicate to perform some task

- Modes of communication
  - Message passing
  - Distributed Shared Memory

Major Components

- Machines/Devices (PCs, servers, specialized devices….)
  - Commonly called nodes
- Network (links, switches, routers….)
- Storage (local, distributed)
- Systems software/applications/tools (Distributed OS, databases/filesystems, load balancer, event/performance monitoring tools, security software…)
  - Not all distributed system will need all
- Middleware
- User applications

Advantages

- Resource Sharing
  - Example: share devices, software, services…across networks
- Better Performance
  - Example: Parallel execution of tasks, load sharing between multiple servers, data replication closer to user….
- Fault Tolerance
  - Example: Increase system availability by putting redundant/backup servers
- Handle inherently distributed data
  - Example: Internet routing, distributed data mining
- Scalability
  - Example: add more servers as needed if load increases

Common Characteristics

- Heterogeneous in many cases
  - Different architectures, operating systems….
- Can be geographically distributed
  - Network delays play an important role
- Faults are common
  - Larger the system is, more chance of something failing at any one time
- Replication is very widely used for better availability and performance
  - Need for maintaining data consistency
  - Trade-off between performance and consistency

Examples of Distributed Systems

- Almost every large system that you use is distributed
  - Online stores like Amazon, Flipkart,….
  - Content delivery services like Netflix, Hotstar,…..
  - Social networks like Facebook, Twitter,…
  - Google and its services
  - Cloud Services like Amazon AWS, Microsoft Azure
  - Travel/Ticket booking services like IRCTC, makeMyTrip, …
  - Your IIT Kgp ERP ☺
  - Internet!
  - Many others…..
- Not all build/manage their own distributed systems, rather use services provided by others. We will learn more later

Why are They Harder to Design?

- Lack of global shared memory
  - Hard to find the global system state at any point
- Lack of global clock
  - Events cannot be started at the same time
  - Events cannot be ordered in time easily
- Hard to verify and prove
  - More complex atomicity issues
  - Arbitrary interleaving of actions makes the system hard to verify
    - Same problem is there for multi-process programs on a single machine
    - Harder here due to communication delays

Example: Lack of Global Memory

- Problem of Distributed Search
  - A set of elements distributed across multiple machines
  - A query comes at any one machine A for an element X
  - Need to search for X in the whole system
- Sequential algorithm is very simple
  - Search and update done on a single array in a single machine
  - No. of elements also known in a single variable

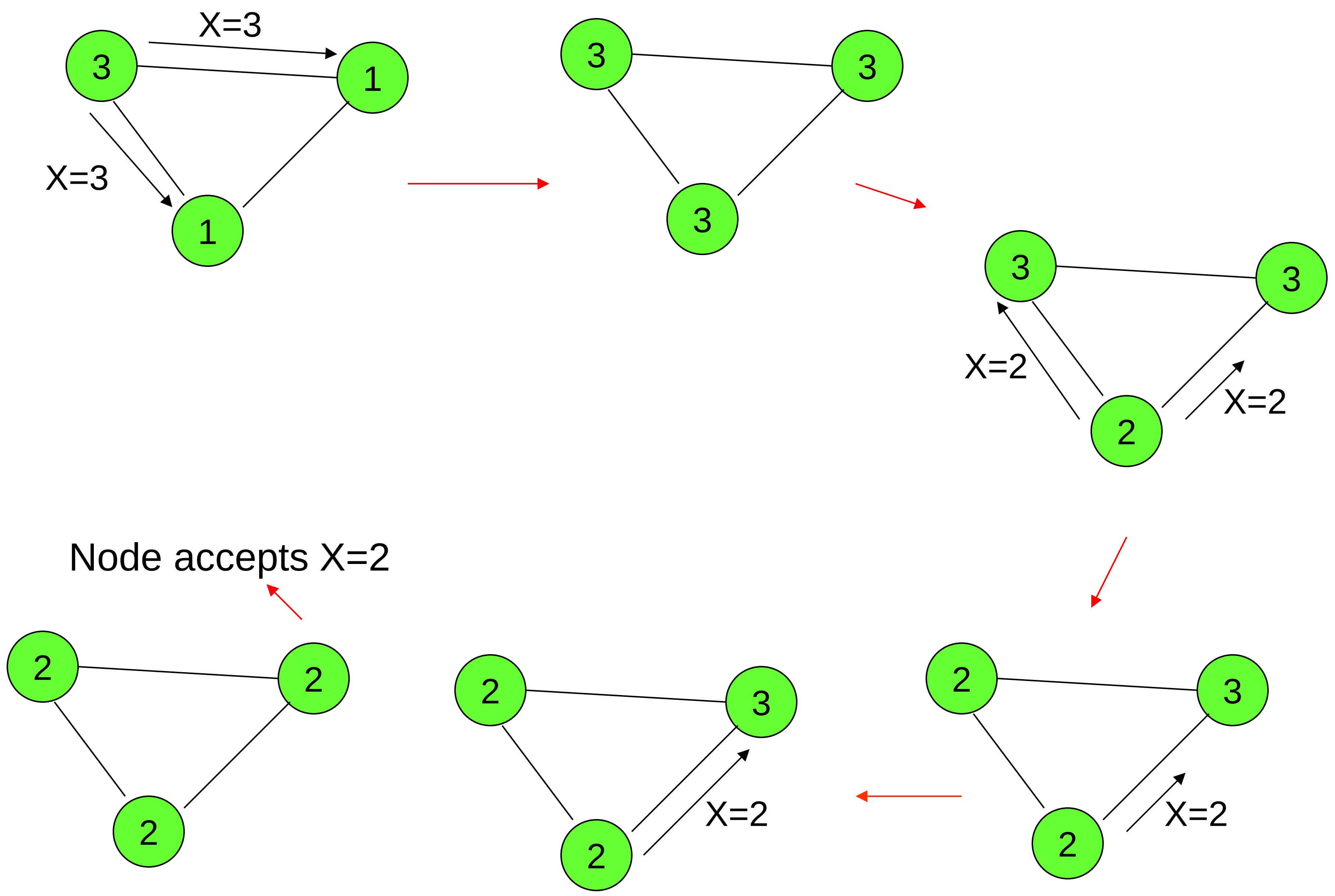
- A distributed algorithm has more hurdles to solve
  - How to send the query to all other machines?
  - Do all machines even know all other machines?
  - How to get back the result of the search in each m/c?
  - Handling updates (both add/delete of elements at a machine and add/remove of machines) – adds more complexity

Main problem

*No one place (**global memory**) that a machine can look up to see the current system state (what machines, what elements, how many elements)*

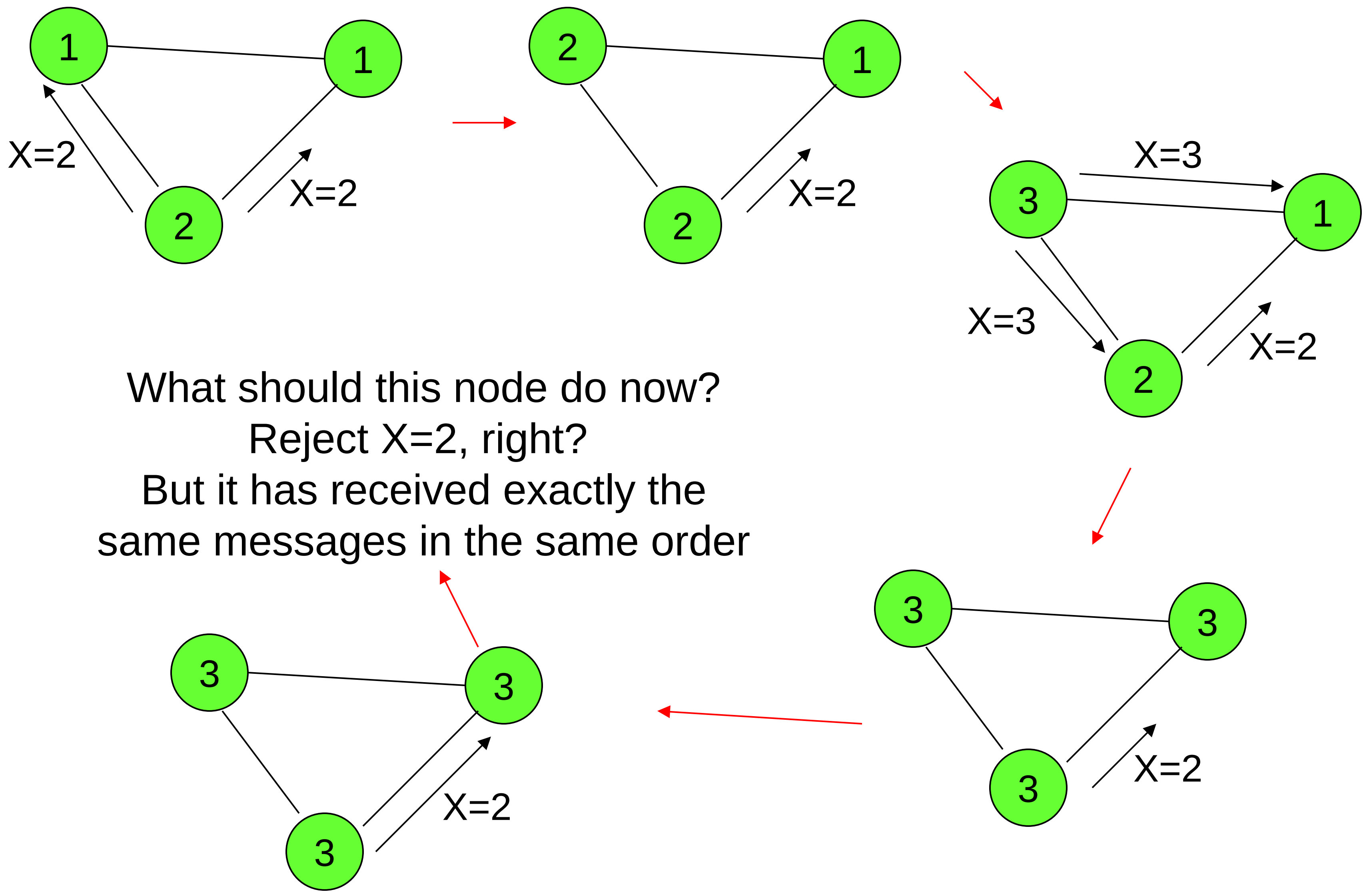
Example: Lack of Global Clock

- Problem of Distributed Replication
  - 3 machines A, B, C have copies of a data X, say initialized to 1
  - Query/Updates can happen in any m/c
  - Need to make the copies consistent within short time in case of update at any one machine
  - Naïve algorithm
    - On an update, a machine sends the updated value to the other replicas
    - A replica, on receiving an update, applies it



X=3
3
1
X=3
1
3
3
3
3
3
X=2
2
X=2
Node accepts X=2
2
2
2
2
3
X=2
2
2
3
X=2
2

But then, consider the following scenario



What should this node do now?
Reject X=2, right?
But it has received exactly the
same messages in the same order

Could be easily solved if all nodes had a synchronized global clock

Example: Atomicity Issues

- Problem of Symmetry Breaking
  - 2 nodes, each with a value 1
  - Need to get to a final state with one node having value 0 and one node having value 1
  - Algorithm
    - Each node sends a message to the other to know its value
    - Each node sets its own value to the complement of the value received from the other node if the two values are the same
  - May never terminate if send-receive-set is not atomic
    - Distributed Scheduler (not atomic) vs. Central Scheduler (atomic)
    - Is a central scheduler in a distributed system practical?

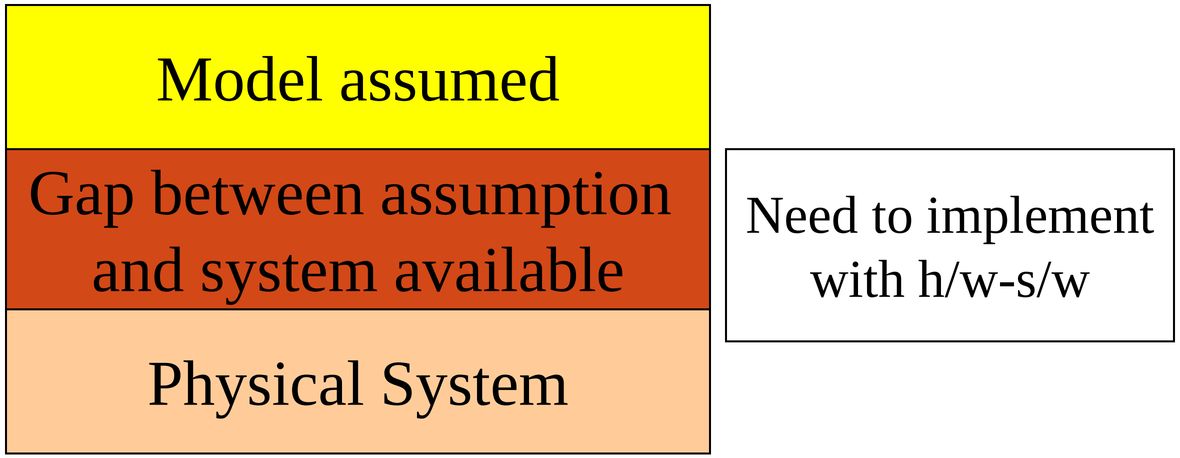
Distributed Algorithms

- Algorithms that run on distributed systems ☺
  - Algorithms in which every node executes some program to cooperatively do something
  - Program run by each node may or may not be the same
- Distributed algorithms have been designed for many many problems
  - For any problem you know, you can ask "is there a distributed algorithm for it?"
- Systems can not run without algorithms, so in any distributed system you see, there are distributed algorithms
- We will look at both algorithms and system issues

Models for Distributed Algorithms

- Informally, guarantees that one can assume the underlying system will (or will not!) give
  - Topology : completely connected, ring, tree, arbitrary,…
  - Communication : shared memory/message passing (Reliable? Delay? FIFO? Broadcast/multicast?…)
  - Synchronous/asynchronous
  - Failure possible or not
    - What all can fail?
    - Failure models (crash, omission, Byzantine, timing,…)
  - Unique Ids
  - Other Knowledge : no. of nodes, diameter
  - Scheduler: Distributed, Central, …

- Less assumptions => weaker model
- A distributed algorithm needs to specify the model on which it is supposed to work
- The model may not match the underlying physical system always


Model assumed
Gap between assumption and system available
Physical System
Need to implement with h/w-s/w

Complexity Measures

- Message complexity : total no. of messages sent
- Communication complexity/Bit Complexity : total no. of bits sent
- Time complexity : For synchronous systems, no. of rounds. For asynchronous systems, different definitions are there
- Space complexity : total no. of bits needed for storage at all the nodes

Example: Distributed Search Again

- Assume that all elements are distinct
- Network represented by graph G with n nodes and m edges

Model 1

Asynchronous, completely connected topology, reliable communication

- Algorithm:
  - Send query to all neighbors
  - Wait for reply from all, or till one node says Found
  - A node, on receiving a query for X, does local search for X and replies Found/Not found.
- Worst case message complexity = 2(n – 1) per query

Model 2

Asynchronous, completely connected topology, unreliable communication

- Algorithm:
  - Send query to all neighbors
  - Wait for reply from all, or till one node says Found
  - A node, on receiving a query for X, does local search for X and replies Found/Not found.
  - If no reply within some time, send query again
- Problems!
  - How long to wait for? No bound on message delay!
  - Message can be lost again and again, so this still does not solve the problem.
  - In fact, impossible to solve (may not terminate)!!

Model 3

Synchronous, completely connected topology, reliable communication

- Maximum one-way message delay = α
- Maximum search time at each m/c = β
- Algorithm:
  - Send query to all neighbors
  - Wait for reply from all for T = $2\alpha + \beta$, or till one node says Found
  - A node, on receiving a query for X, does local search for X and replies Found if found, does not reply if not found
  - If no reply received within T, return "Not found"
  - Message complexity = n -1 if not found, n if found
  - Message complexity reduced, possibly at the cost of more time

Model 4

Asynchronous, reliable communication, but not completely connected

- How to send the query to all?
- Algorithm (first attempt):
  - Querying node A sends query for X to all its neighbors
  - Any other node, on receiving query for X, first searches for X. If found, send back "Found" to A. If not, send back "Not found" to A, and also forward the query to all its neighbors other than the one it received from (flooding)
  - Eventually all nodes get it and reply
  - Message complexity – O(nm) (why?)

- But are we done?
  - Suppose X is not there. A gets many “Not found” messages. How does it know if all nodes have replied? (*Termination Detection*)
- Lets change (strengthen) the model
  - Suppose A knows n, the total number of nodes
    - A can now count the number of messages received. Termination if at least one “Found” message, or n “Not found” messages
    - Message complexity – O(nm)
  - Suppose A knows upper bound on network diameter and synchronous system
    - Can be done with O(m) messages only
- Can you do it without changing the model?

So Which Model to Choose?

- Ideally, as close to the physical system available as possible
  - The algorithm can directly run on the system
- Should be implementable on the physical system by additional h/w-s/w
  - Ex., reliable communication (say TCP) over an unreliable physical system
- Sometimes, start with a strong model, then weaken it
  - Easier to design algorithms on a stronger model (more guarantees from the system)
  - Helps in understanding the behavior of the system
  - Can use this knowledge to then design algorithms on the weaker model