COMP4137 Blockchain Technology and Applications
COMP7200 Blockchain Technology

Lecturer: Dr. Hong-Ning Dai (Henry)

Lecture 3

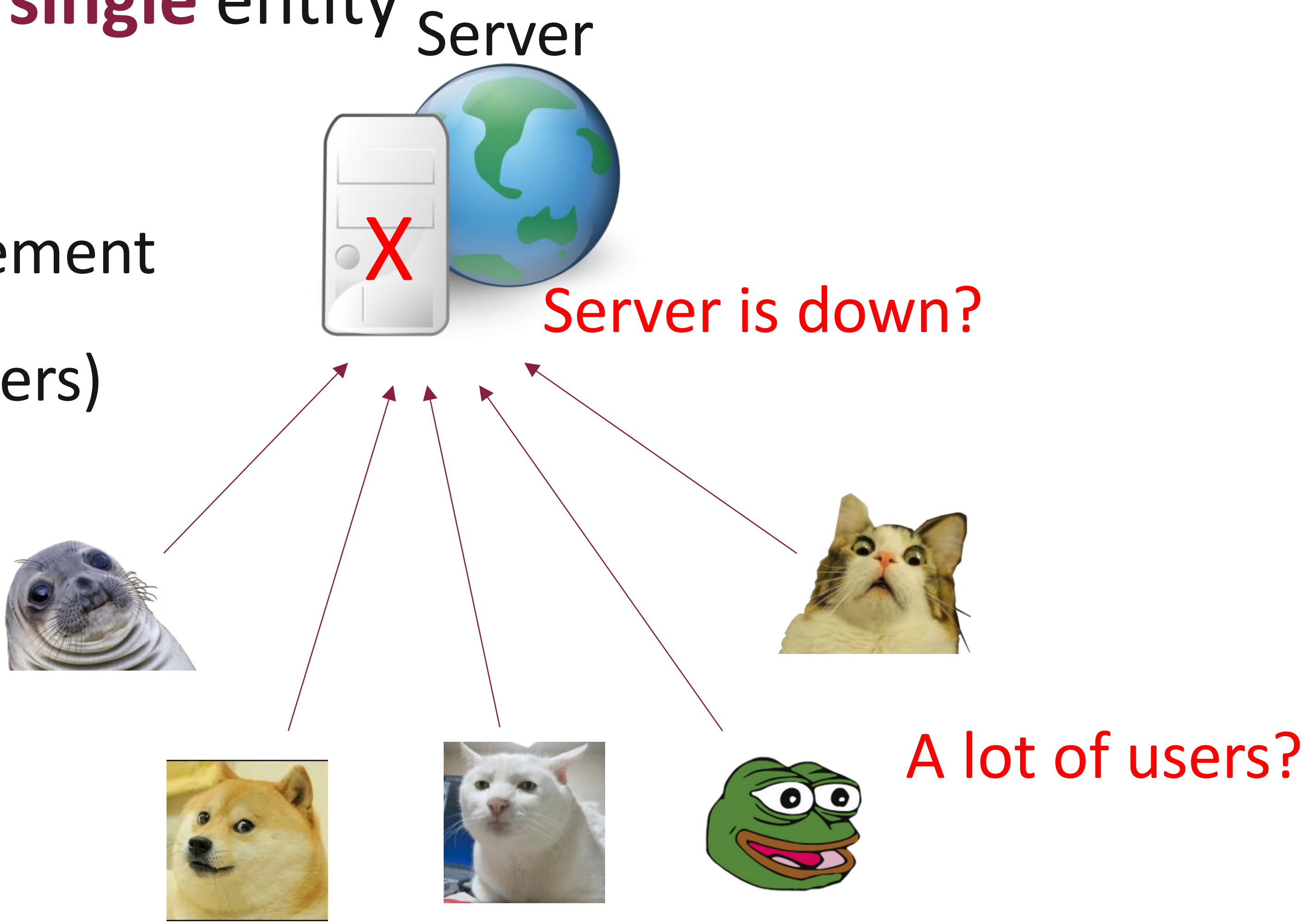
Distributed System and Consensus

Outline

- Definition and Characteristics
- Architecture Models
- Distributed Algorithms

Centralized Systems

- All tasks completed by a **single** entity
  - ✓ Simple
  - ✓ Easy to design and implement
  - ✓ Efficient (with small # users)

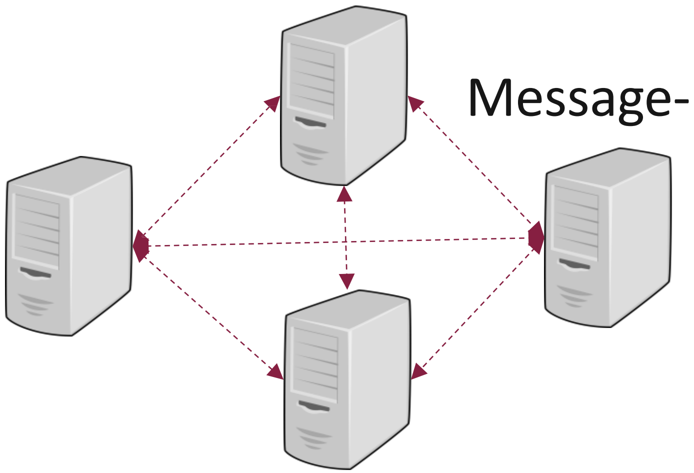


Distributed Systems

- A group of independent entities communicated with one another in a coordinated manner
- Collaboratively enable a service (computing, data sharing and storage)
- **Goal:** Address inherent limitations of centralized systems
  - Robustness
  - Scalability
  - Reliability

Distributed Systems

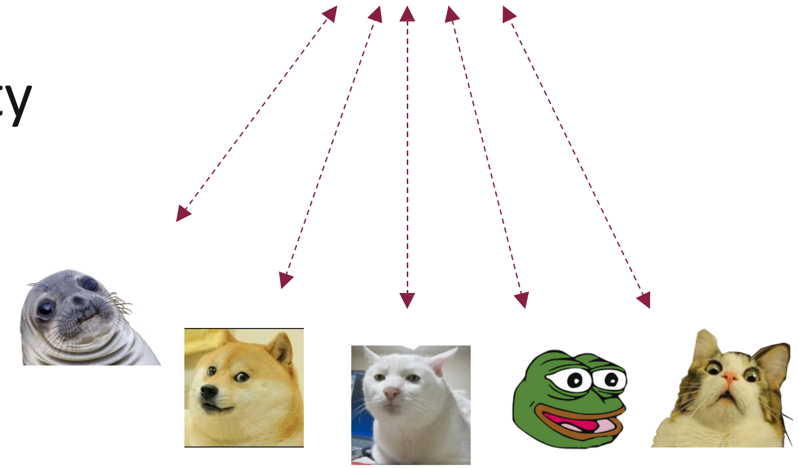
Distributed server



Message-based communication

Each entity has separate resource (data, memory, processor, OS)

Appeared as a single entity



Key Characteristics

- **Transparency**
  - Most important feature
  - Illusion of a single system
    - Hide all internal organization, communication details
    - Uniform interface
  - Access transparency, location transparency, relocation transparency, migration transparency, replication transparency, concurrency transparency, failure transparency, scaling transparency, performance transparency

Key Characteristics

- **Openness**
- **Heterogeneity**
    - Variety and differences in hardware and software components
- **Resource Sharing**
    - Resources (hardware, software, data) accessed across multiple entities
- **Concurrency**
    - Parallel executions of activities
    - Reduce latency, increase throughput

Key Characteristics

- **Scalability**
  - Add/remove components to/from the system
- **Fault Tolerance**
  - Continuous availability

Design Goals

- **High Performance**
  - Low latency, high throughput
- **Reliability**
  - Preserve correctness and integrity in the presence of faulty/malicious nodes
  - Failure detection, self-stabilization
- **Scalability**
  - Adapt with flexible number of users in the system

Design Goals

- **Consistency**
  - Update consistency, replication consistency, cache consistency, failure consistency, clock consistency, user interface consistency
  - Synchronization between concurrent tasks
- **Security**
  - Malicious adversaries, secure communication, resource protection

CAP Theorem

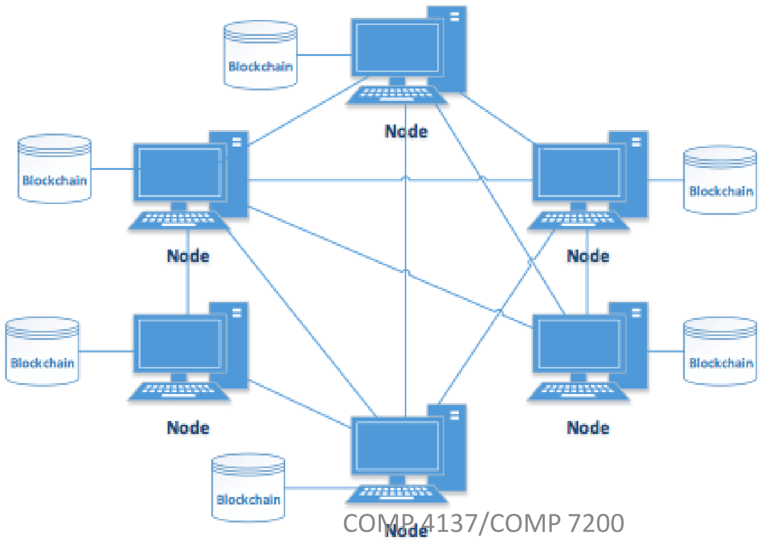
> *"Any distributed system cannot achieve Consistency, Availability and Partition tolerance concurrently."* -- Gilbert and Lynch

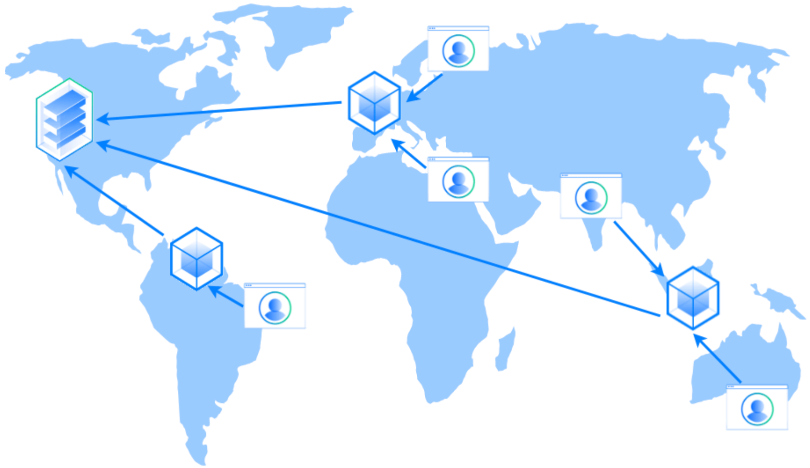
- **Consistency**
  - All nodes see the same data at the same time
- **Availability**
  - If the node in the system does not fail, it must always respond to the user's request.
- **Partition tolerance**
  - The network will be allowed to lose arbitrarily many messages sent from one node to another

Choose 2 out of 3: Generally between consistency & availability under partition!

Distributed System Applications

- <u>Distributed systems are everywhere</u>
  - Mobile systems
  - Sensor networks IoT
  - Ubiquitous and Pervasive computing WWW
  - P2P computing



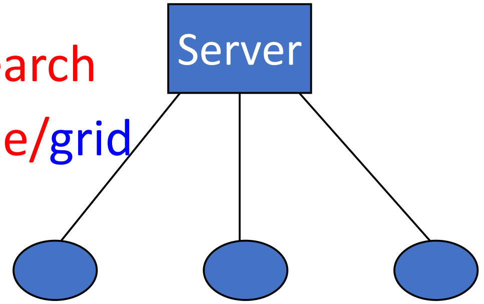


Content Delivery Network (CDN)

Peer-oriented Systems

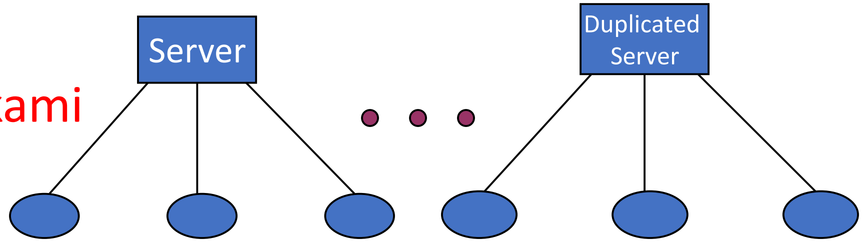
Client/server

a search engine/grid

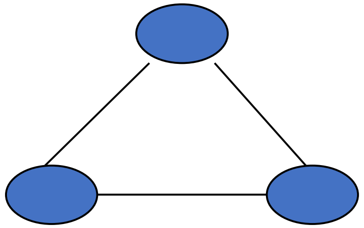


Content Delivery Networks

e.g. Akami



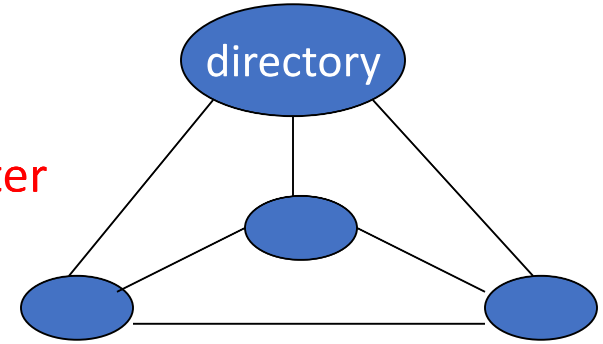
Pure P2P



e.g. Freenet & Gnutella

Hybrid P2P

e.g. Napster



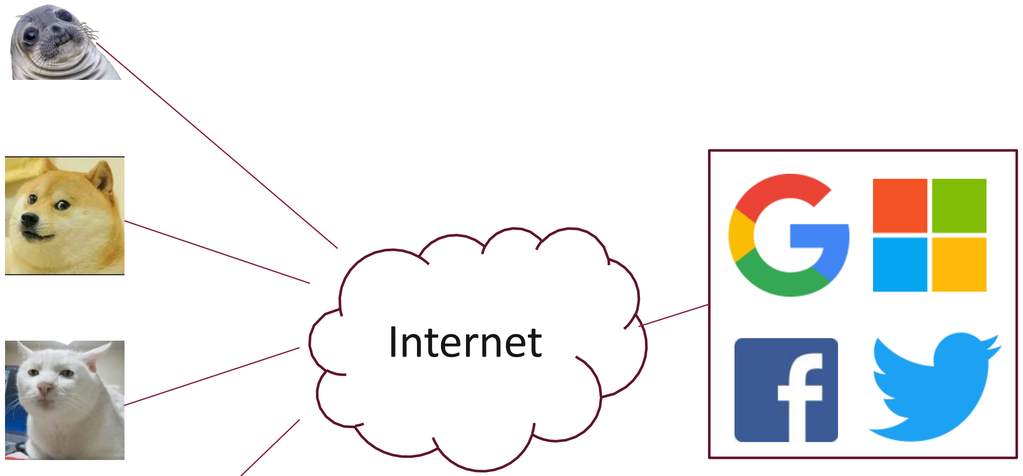
Outline

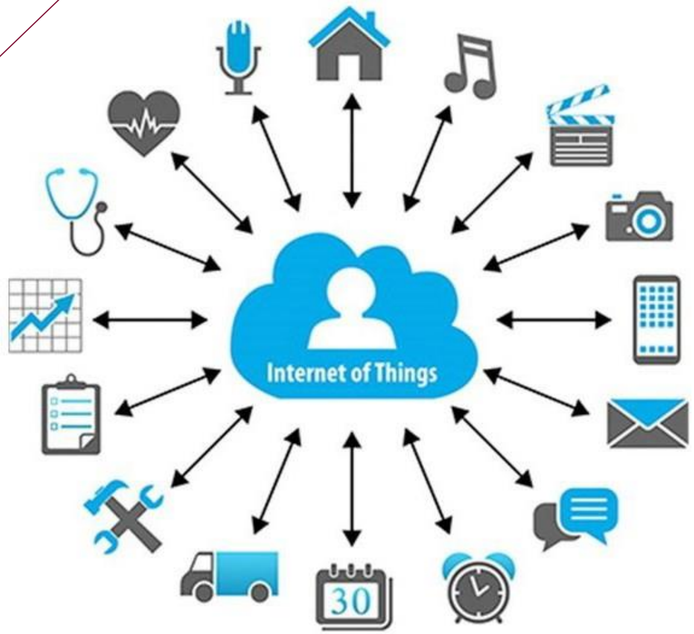
- Definition and Characteristics
- Architecture Models
- Distributed Algorithms

Client-Server Architecture

- Basic model
- Two types of node: client (slave) and server (master)
- All tasks accomplished by server
  - Server is resource-powerful

    Client is resource-limited
- Asymmetric, partially distributed
- <u>Examples:</u> Cloud services (Amazon, MS, Facebook, Google), IoTs





Client-Server Architecture

- **Advantage**
  - Easy to maintain security and reliability
  - Enable a wide range of services
  - Easy to design and implement

Client-Server Architecture

- **Disadvantages**
  - Central point of failure and compromise

    Attacks targeting to server nodes (e.g., DoS, data-breach)

  - Resource management and administration
  - Central point of trust

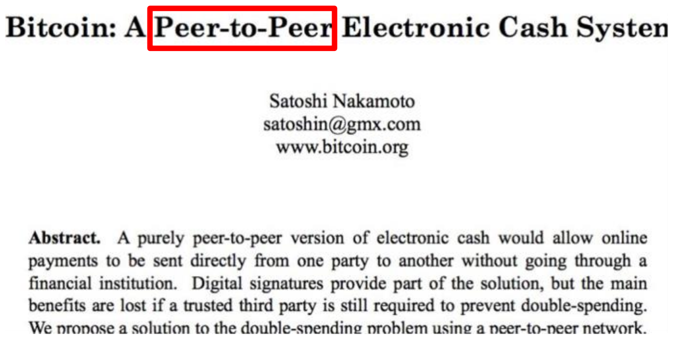
    Server has more control and authority in the system

  - Not so scalable

    More clients join, more server demands

Peer-to-Peer Architecture

- A network of nodes (peers) sharing resources directly with each other
- **Symmetric:** All nodes are <u>equal participants</u> and play both roles: provider and consumer of resource
    - No *server* node
- Fully distributed, no centralized data and resource
    - “The ultimate form of democracy on the Internet”
- <u>Examples:</u> blockchains, vehicular network, file-sharing



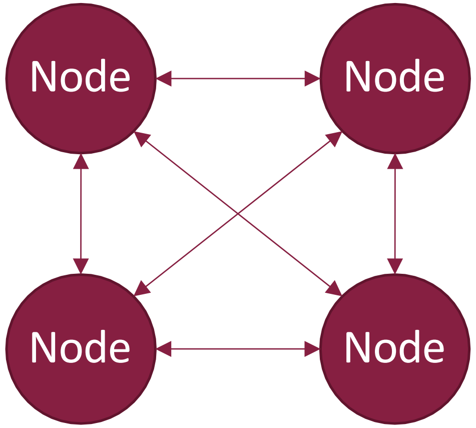
Bitcoin: A Peer-to-Peer Electronic Cash Systen

Satoshi Nakamoto
satoshin@gmx.com
www.bitcoin.org

Abstract. A purely peer-to-peer version of electronic cash would allow online payments to be sent directly from one party to another without going through a financial institution. Digital signatures provide part of the solution, but the main benefits are lost if a trusted third party is still required to prevent double-spending. We propose a solution to the double-spending problem using a peer-to-peer network.

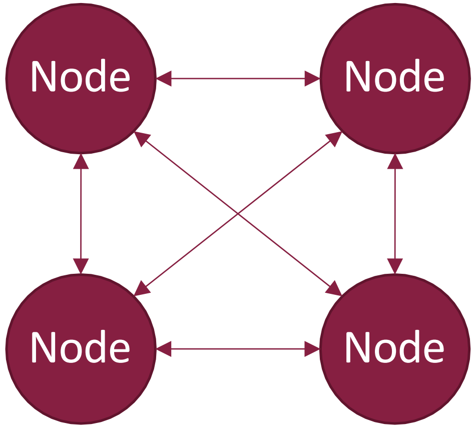
Peer-to-Peer Architecture

- **<u>Advantage</u>**
  - Distributed trust
  - Balanced resource load
  - High resource capacity and high scalability
    - More clients, more servers
  - High fault-tolerance and resiliency against DoS attacks



Peer-to-Peer Architecture

- **Disadvantage**
  - Costly backup, high bandwidth consumption
  - Hard to control
  - Hard to maintain security and consistency
    - Vulnerable to network partitions, byzantine behavior
  - Unstable



Distributed vs. Decentralized

- P2P is distributed, but offers various degrees of decentralization
- Some P2P still need central authorities to make decision (e.g., network control, resource load) efficiently
    - Somewhat centralized
- Decentralized is <u>NOT all-or-nothing</u>

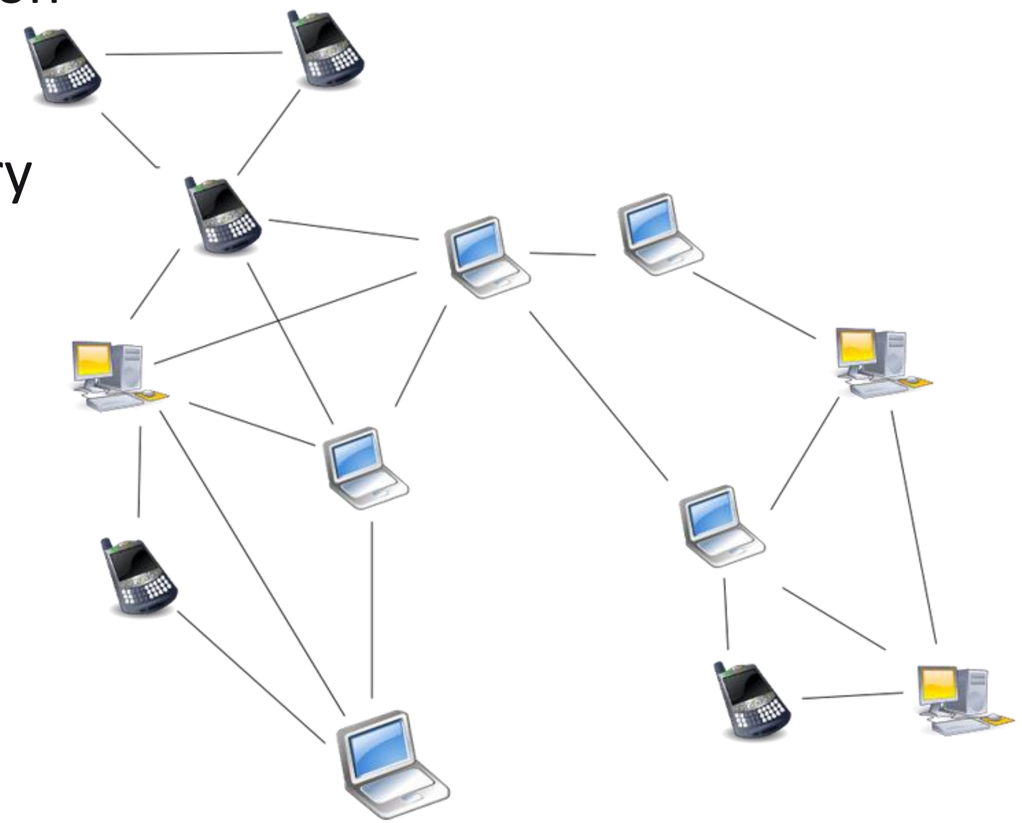
Distributed vs. Decentralized

- In fact, no system is purely decentralized, or purely centralized

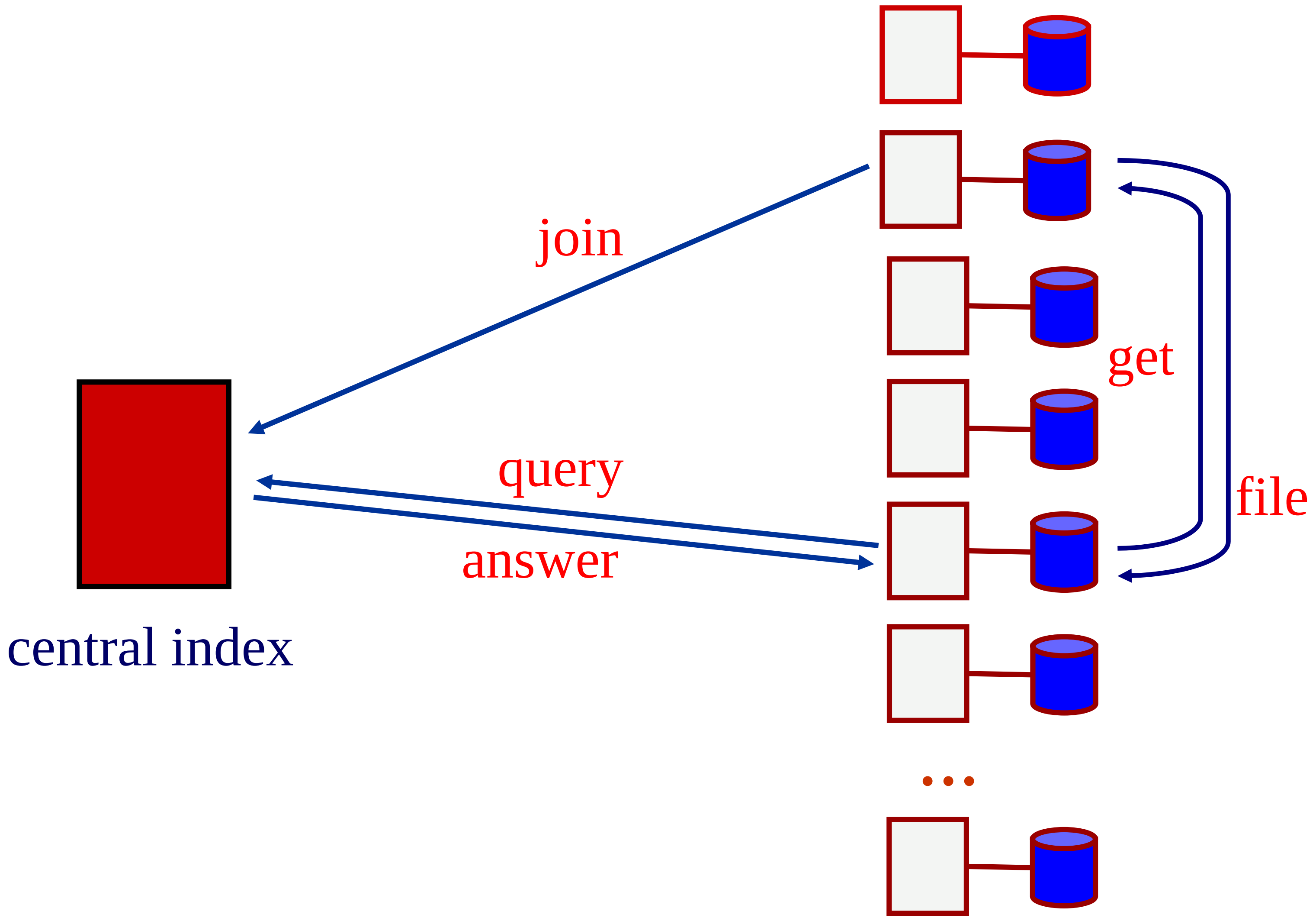
- Blockchain can be centralized or decentralized under certain degrees
    - Depend on the design and application requirements

Unstructured P2P network

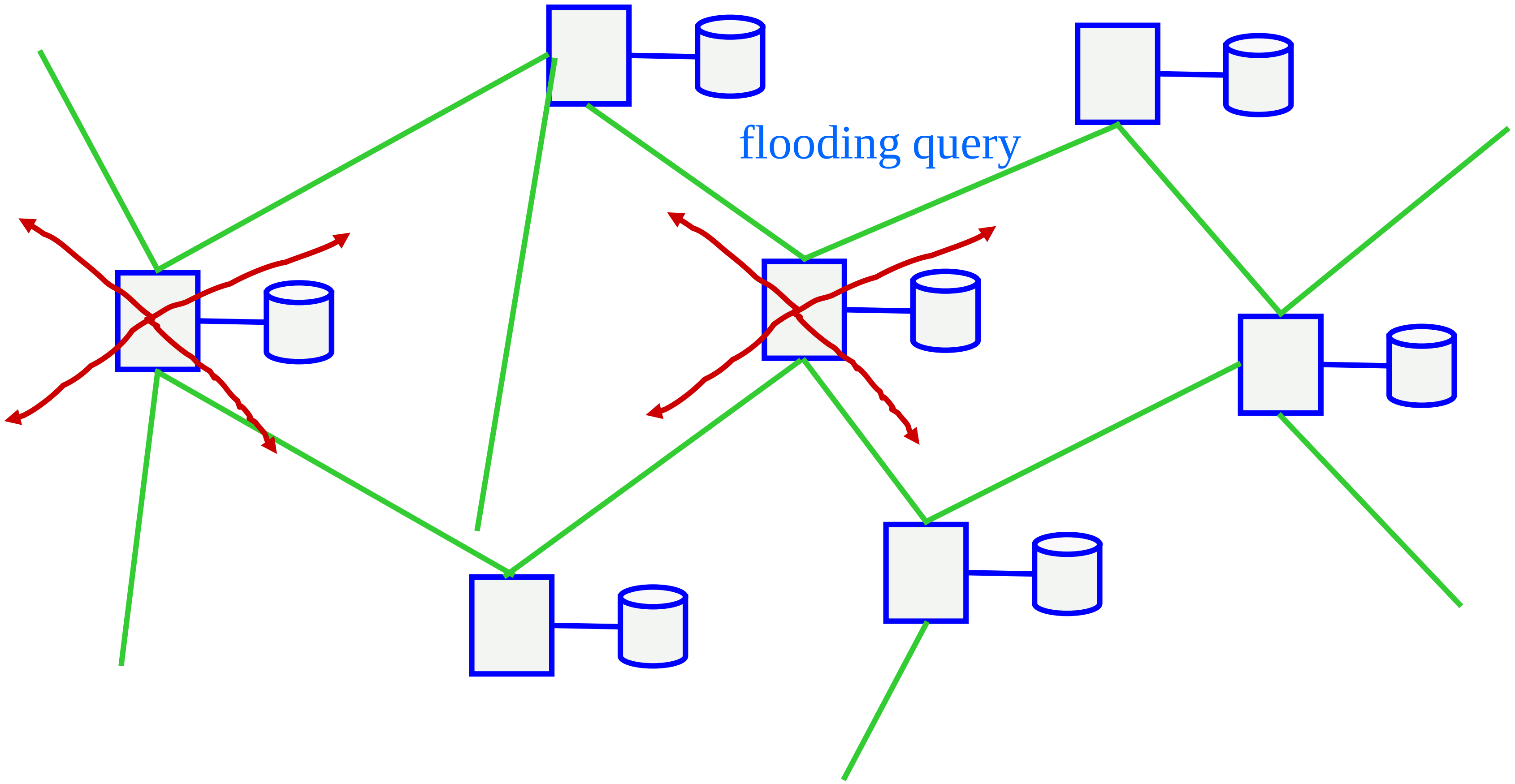
- Easy to build
- Loose restriction on overlay structure, data location and resource distribution
  - Nodes communicate randomly, perform arbitrary tasks
- High resiliency to churn
  - Nodes leave and join frequently
- Nodes and resources are loosely-coupled
  - Data navigation issue
  - High resource (CPU, memory, network) usage
- <u>Example:</u> Napster, Gnutella, KaZaA



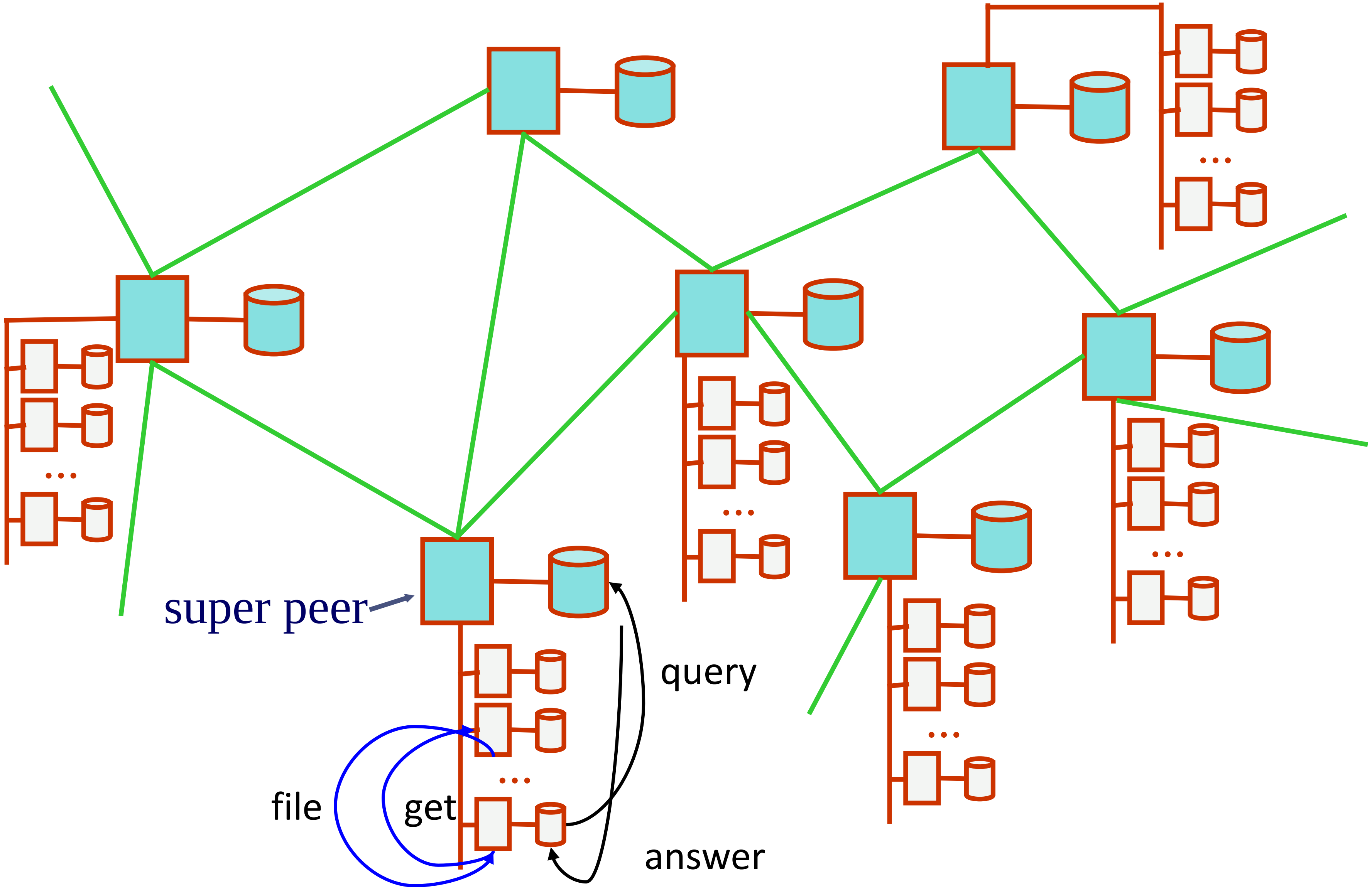
Directory-based P2P of Sharing Music: Napster



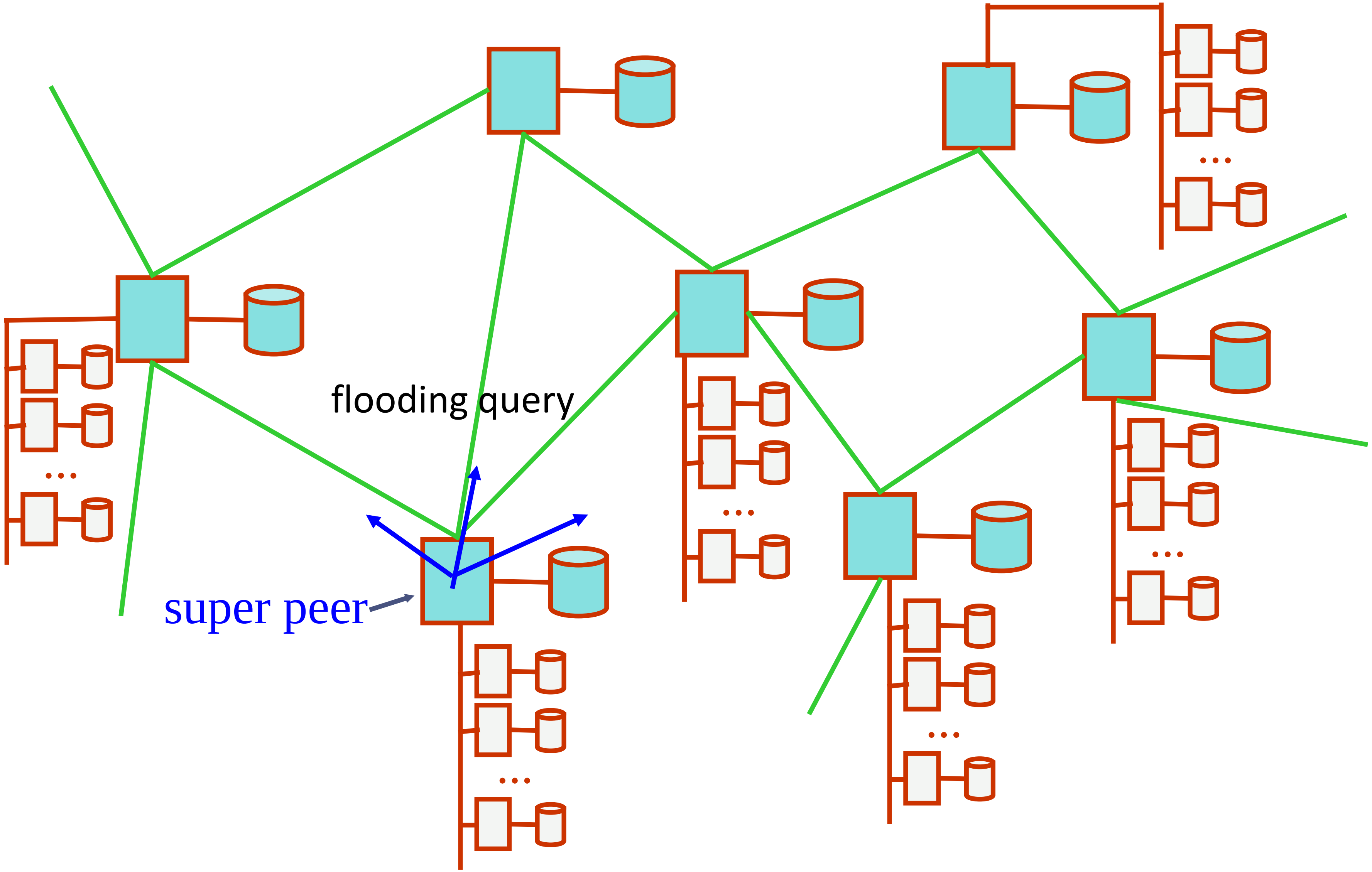
Unstructured P2P: Gnutella



Super Node based P2P: KaZaA (Morpheus)



Super Node based P2P: KaZaA (Morpheus)

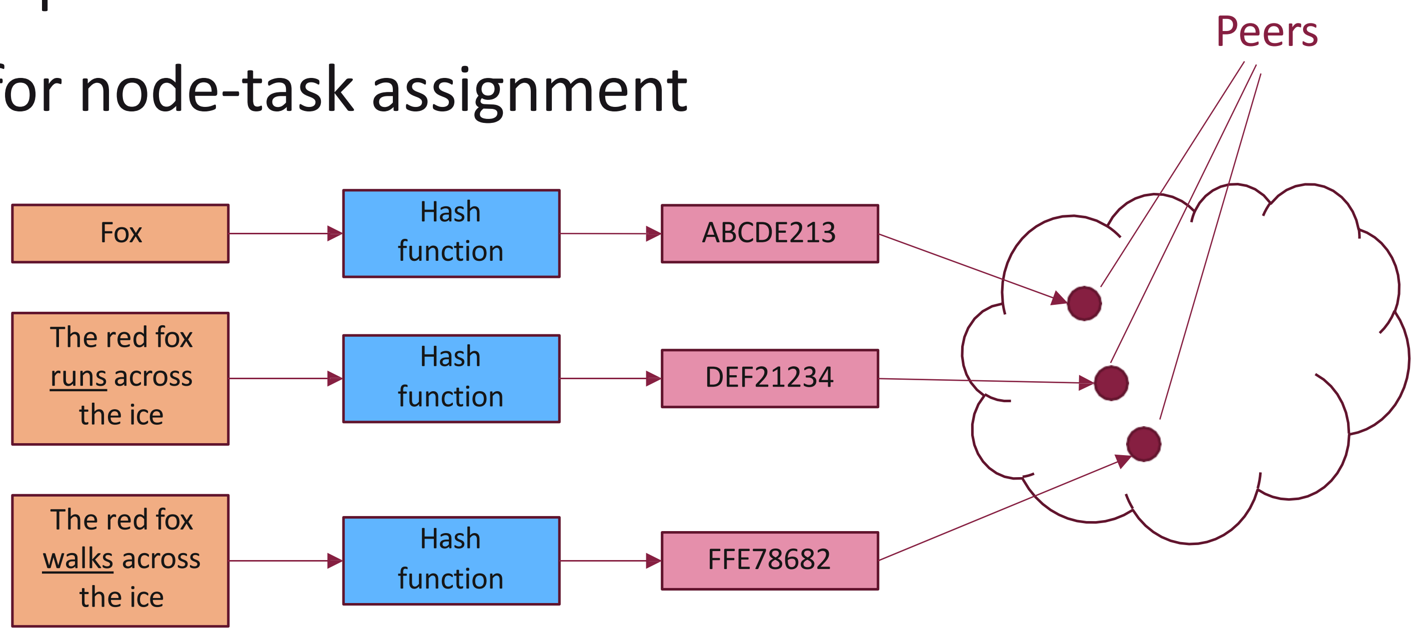


Structured P2P network

- Structured overlay network, restriction on content placement and resource distribution
- Nodes and resources are **tightly-coupled**, everyone has their own task
- Each node is responsible for a specific role in the network
- Distributed Hash Table (DHT) for node-task assignment
- Simplifying content location

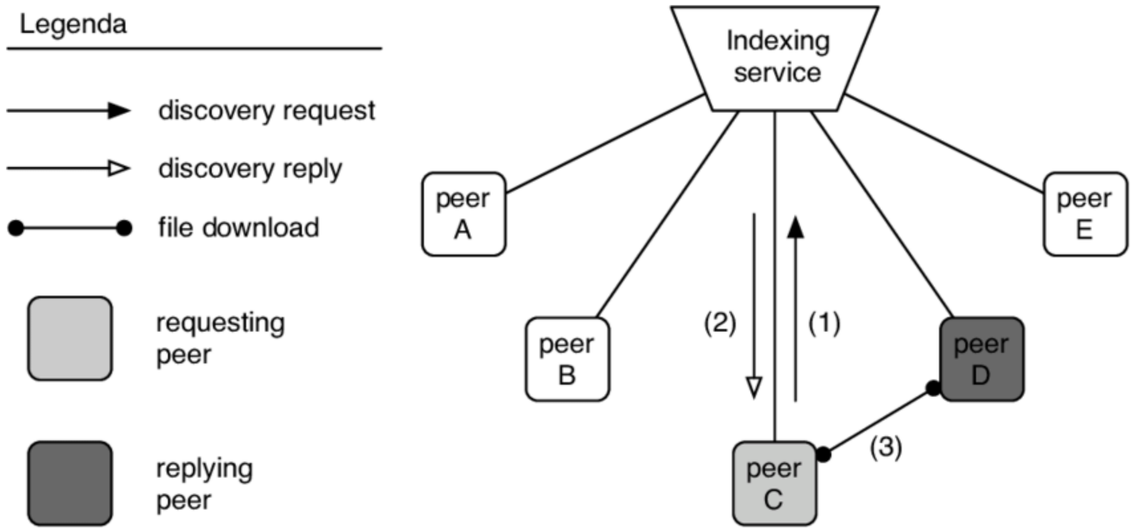
Harder to build

Low resiliency against churn



Hybrid P2P network

- Central authorities to help nodes navigate each other
  - Combine client-server with P2P models
- Tend to improve overall performance
  - Trade-off b/w centralization vs. node equality
- Inherit the best of both worlds
  - Efficiency in C-S setting, and decentralization in P2P setting



Objectives and Benefits of P2P

- As long as there no physical break in the network, the target file will always be found.
- Adding more contents to P2P will not affect its performance. (information scalability).
- Adding and removed nodes from P2P will not affect its performance. (system scalability).

Peer-oriented Applications

- File Sharing: document sharing among peers with no or limited central controls.
- Instant Messaging (IM): Immediate voice and file exchanges among peers.
- Distributed Processing: One can widely utilize resources available in other remote peers.

Outline

- Definition and Characteristics
- Architecture Models
- Distributed Algorithms

What is Consensus?

Consensus is an agreement among a group of people on an idea, statement, or plan of action

- Majority: 51%
- Supermajority: 66% (sometimes higher)
- Unanimous: 100%
- Weighted: not all votes weighed equally

Consensus Mechanism

- Main Motivation: Reliability and Fault-Tolerance in distributed system
  - Correct operation in the presence of corrupted nodes
  - Reach a common agreement in a distributed/ decentralized system
  - Nodes propose values
    - All nodes must agree on one of these values

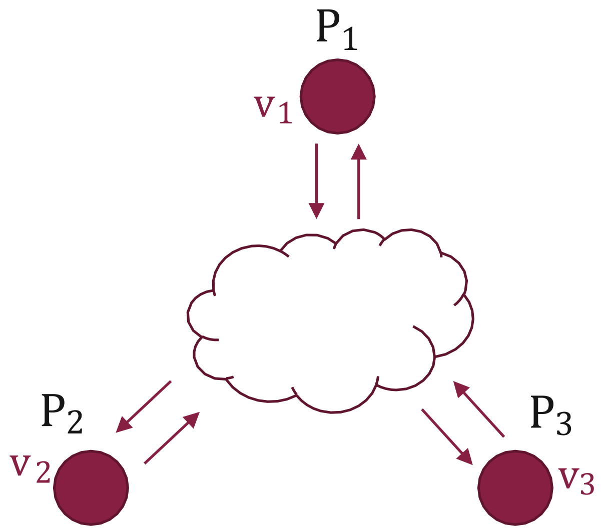
Consensus Mechanism

- Key to solving many problems in distributed computing
  - Atomic commit of database transaction
  - Clock synchronization
  - Dynamic group membership

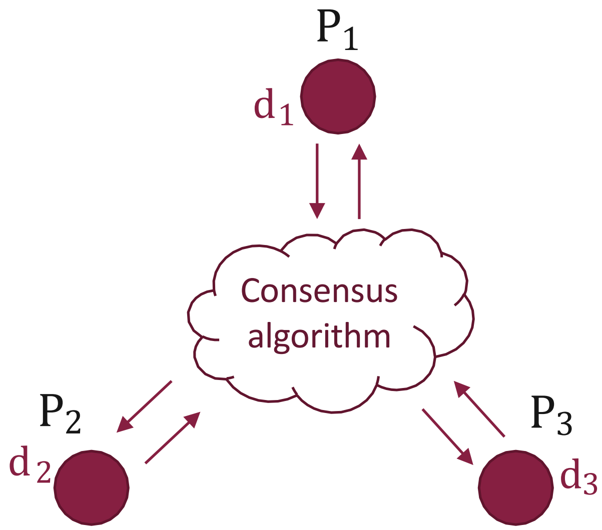
Consensus Protocol: Definition

- <u>A consensus protocol comprises two algorithms:</u>
  - $v_i \leftarrow \text{Propose}()$: Each node n_i proposes a value v_i and broadcasts v_i to the network
  - $v \leftarrow \text{Decide}(v_1, v_2, \dots, v_n)$: All nodes agree on a common value $v \in \{v_1, v_2, \dots, v_n\}$

  - The protocol terminates when all correct nodes decide on the same value
  - The agreed value cannot be arbitrary: it must come from some correct node



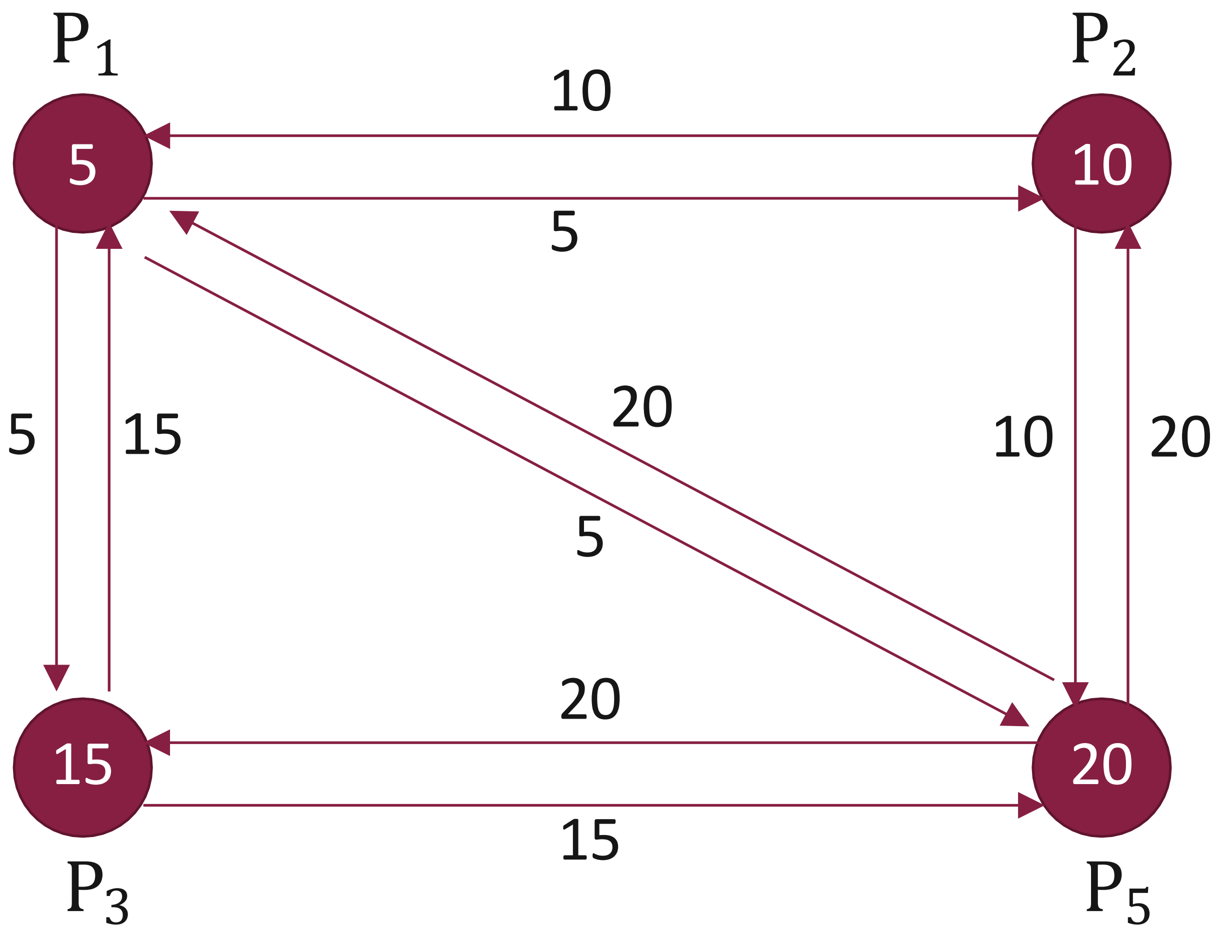
1. Propose



2. Decide

Consensus Protocol

- Example: Find max value among all values



Consensus Properties

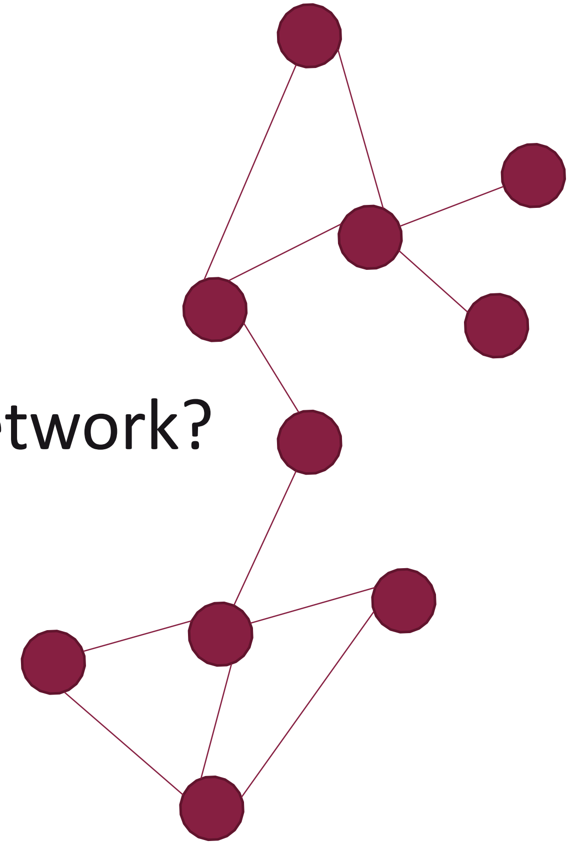
- **Validity**
    - Value agreed is a value proposed
- **Agreement**
    - All correct nodes agree on the same value
- **Integrity**
    - Every correct node decides at most once

Consensus Properties

- **Termination**
  - Every correct node must decide at the end of protocol
- **Safety**
  - Every correct node must not agree on incorrect value
- **Liveness**
  - Every correct value must be accepted

When Failure Happens

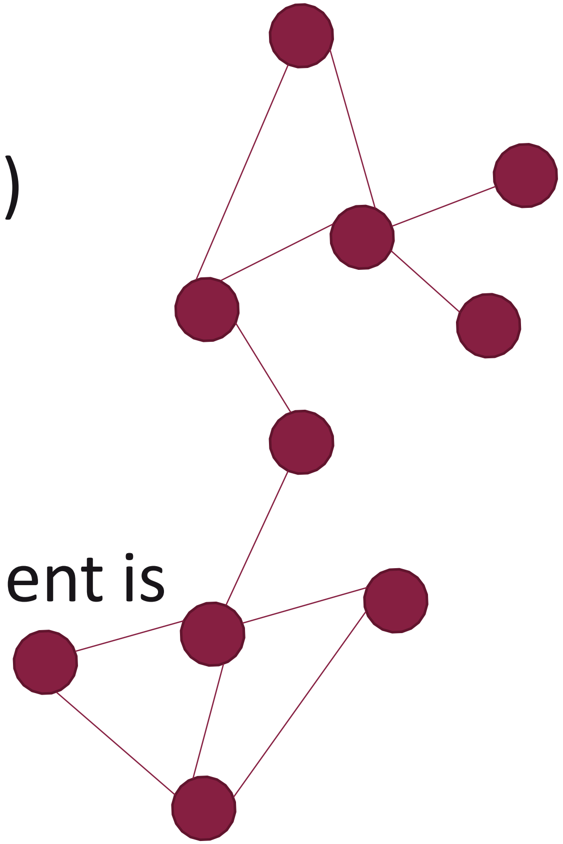
- If no failure or malice, easy to reach a consensus
  - Individuals broadcast their values to all nodes
  - Values received with a pre-defined timeframe (synchronous)



- What if there are failures or malicious activities in the network?

When Failure Happens

- Common types of failure
  - Crash Fault: Node crashed, offline during communication
  - Network Fault: Not all pairs of nodes well- connected (partitioned network), latency (no notion of global time)
  - Byzantine Fault: Nodes may be malicious

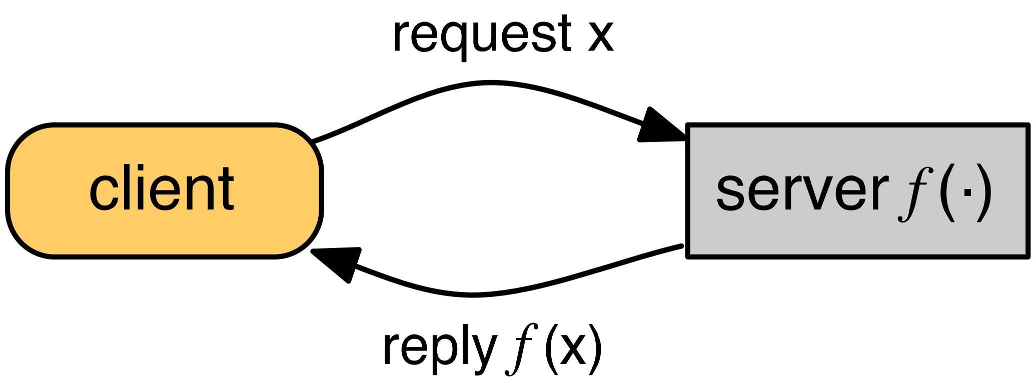


- Achieving consensus in the faulty (yet realistic) environment is hard

Synchronous vs. Asynchronous Systems

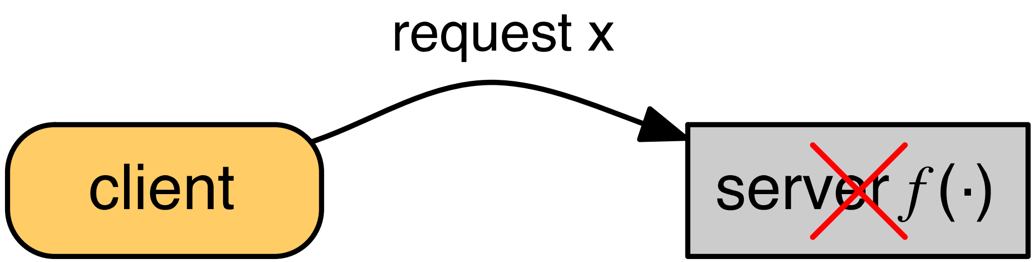
- Synchronous system
  - Defined maximum waiting time for message transmission
  - Easy to reach a consensus
- Asynchronous system
  - Undefined waiting time
  - Hard to achieve a consensus

Single Server Architecture



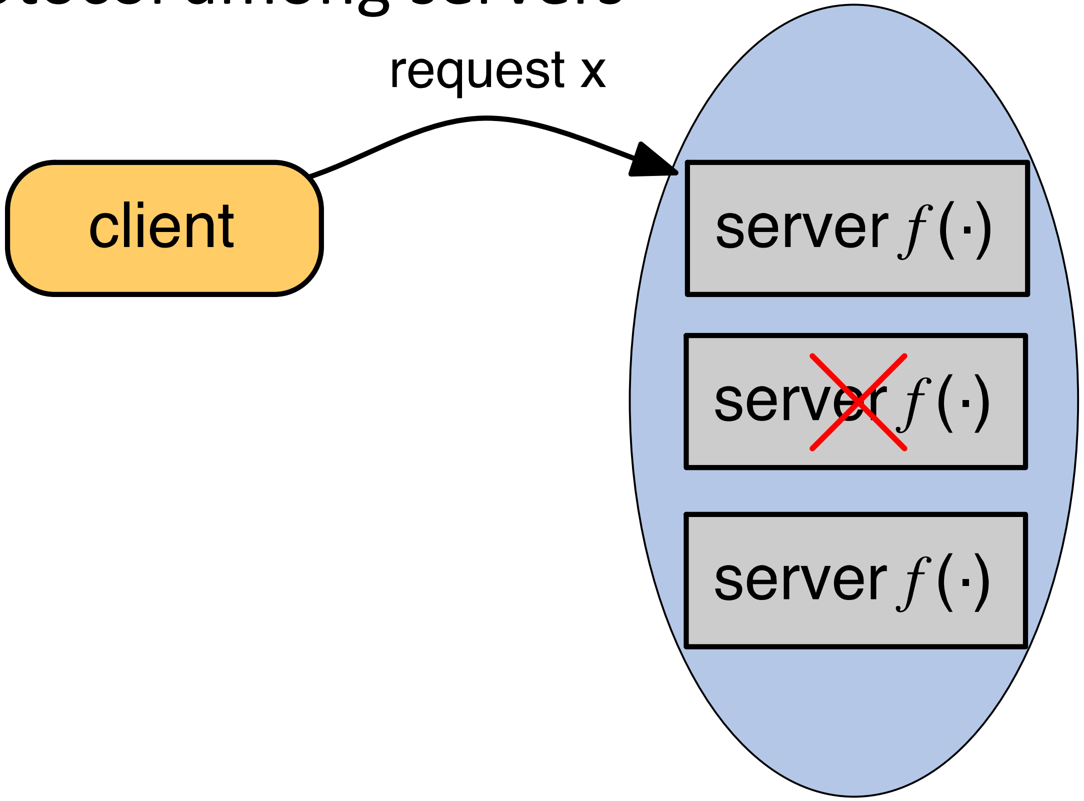
Single Server Architecture

- A single point of failure!



State Machine Replication (SMR)

- Interactive protocol among servers



- State machine replication gives safety and liveness.

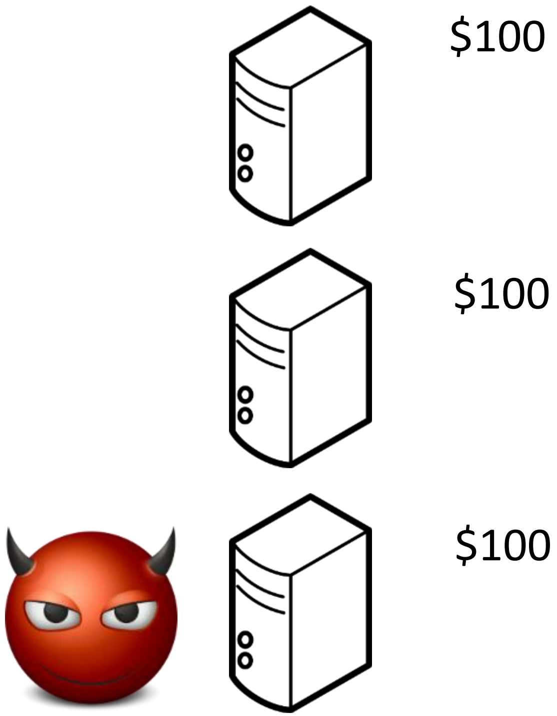
State Machine Replication (SMR)

- Replicas maintain the same state
  - Replicas start in the same state
  - Operations are deterministic
  - Replicas execute operations in the same order (i.e., total order)
- Replicas send replies to clients
- Clients vote on replica replies

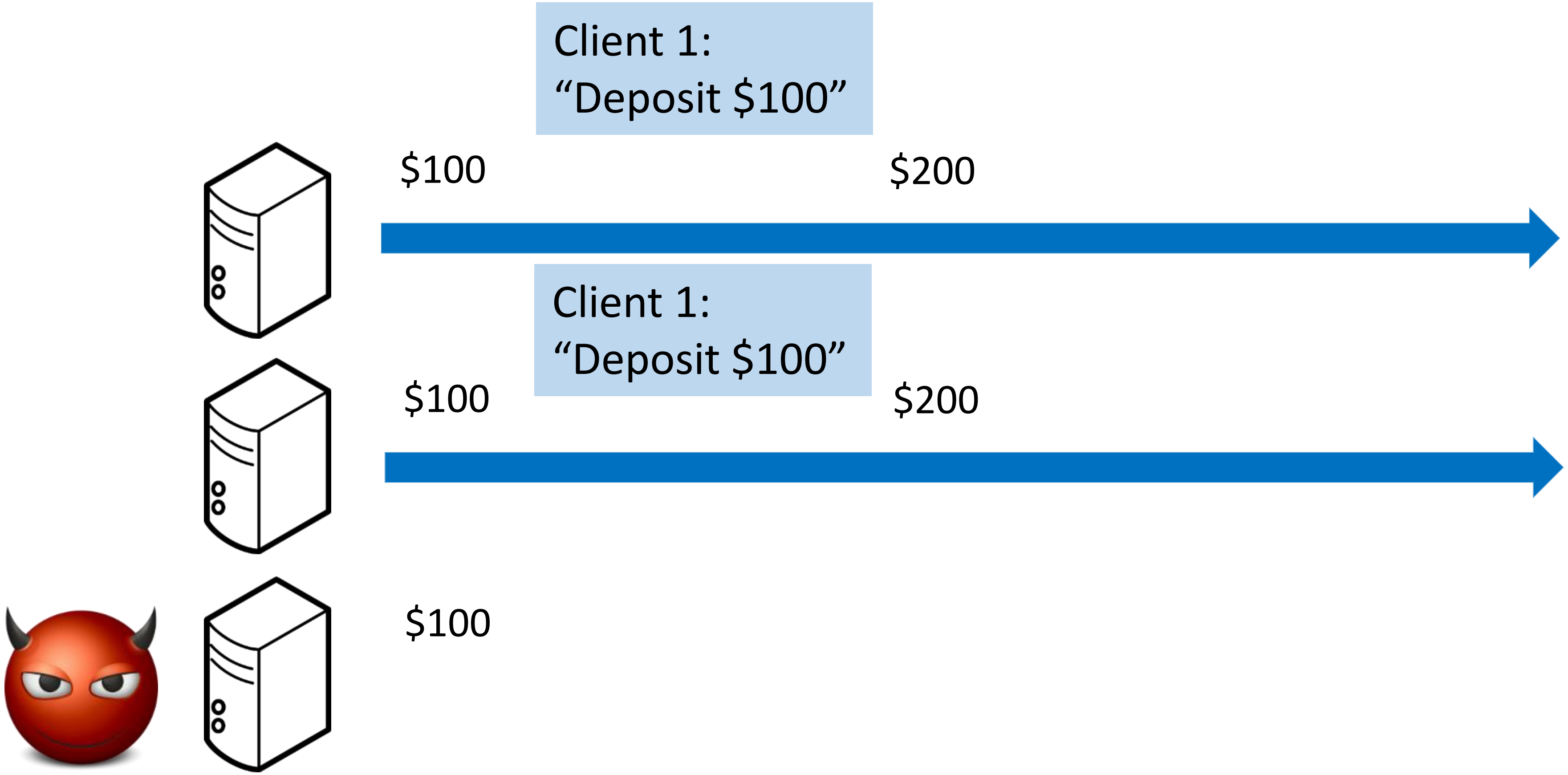
Roughly, Consensus: All About Achieving “Total Order”

[Lamport, ACM TOPLAS 1984]

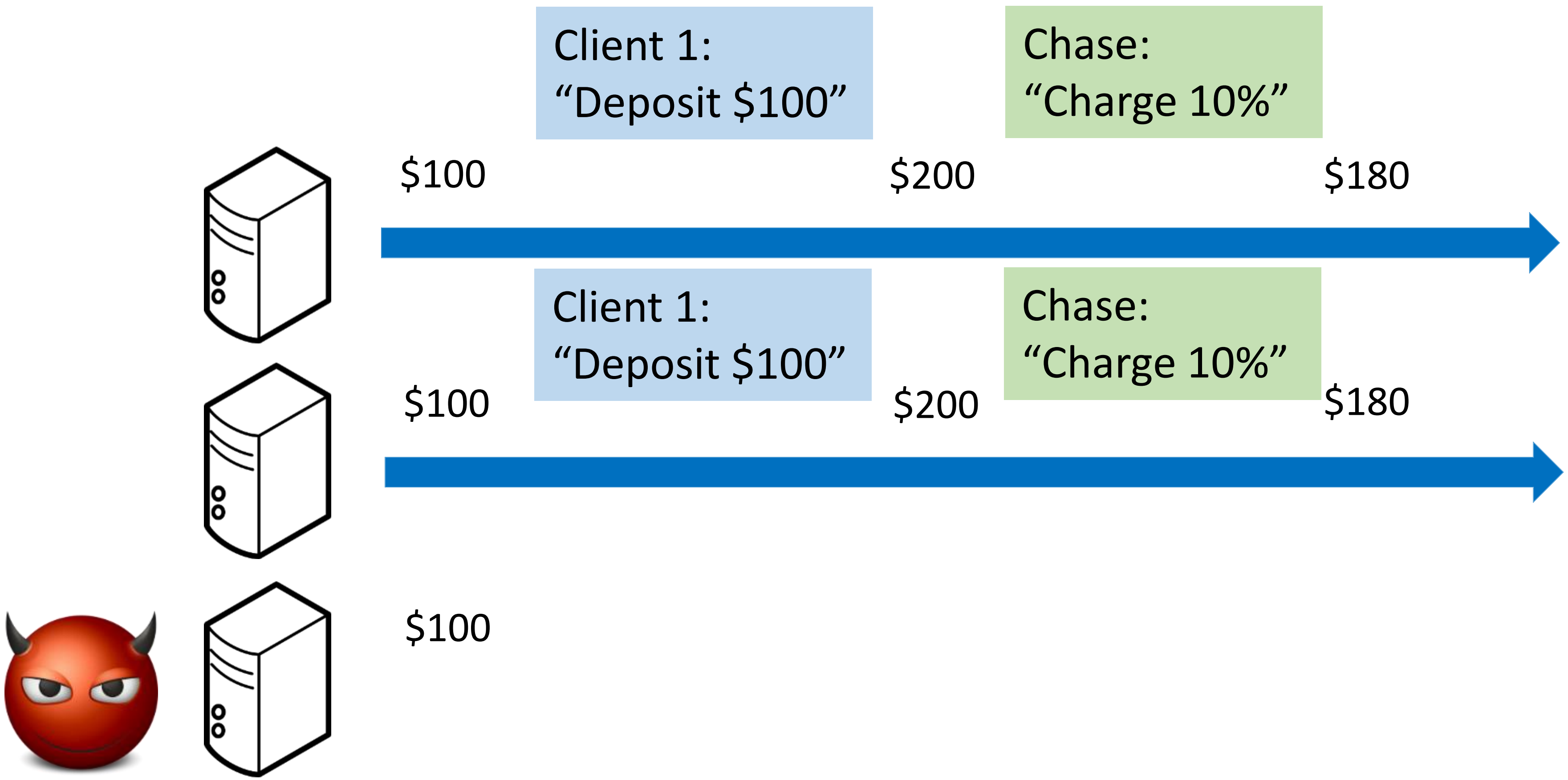
- Blockchains (modeled as state machine replication)



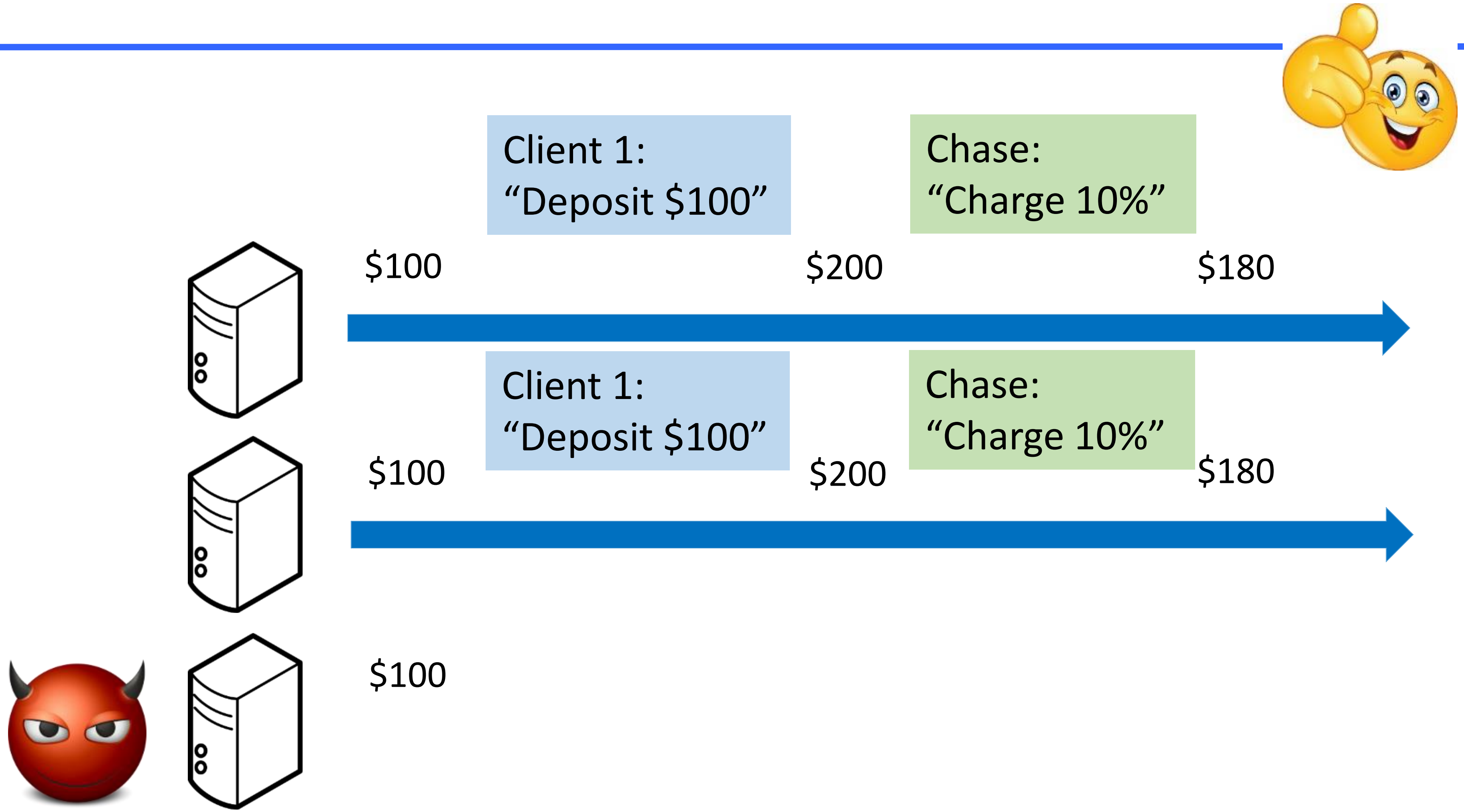
The “Total Order” Requirement



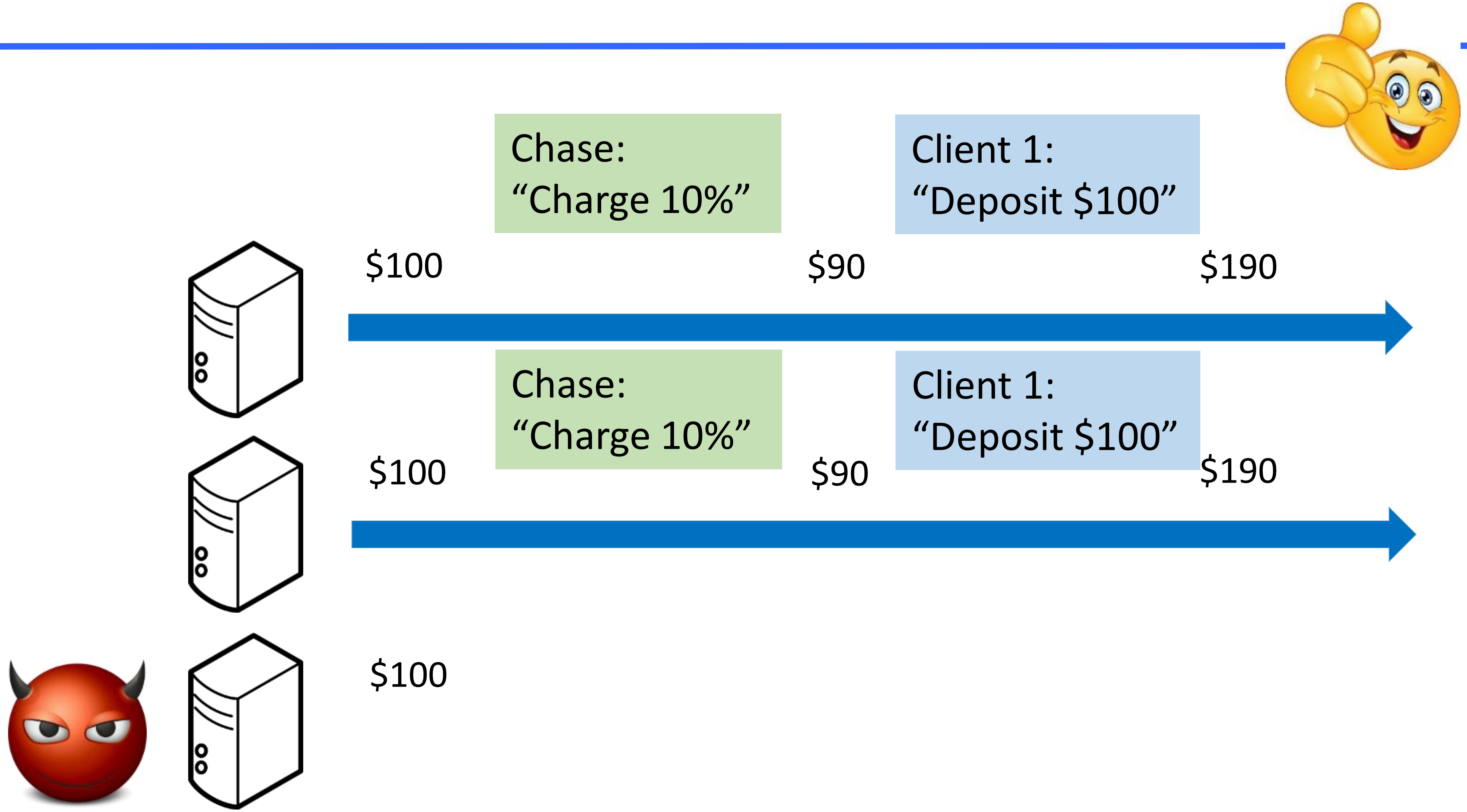
The “Total Order” Requirement



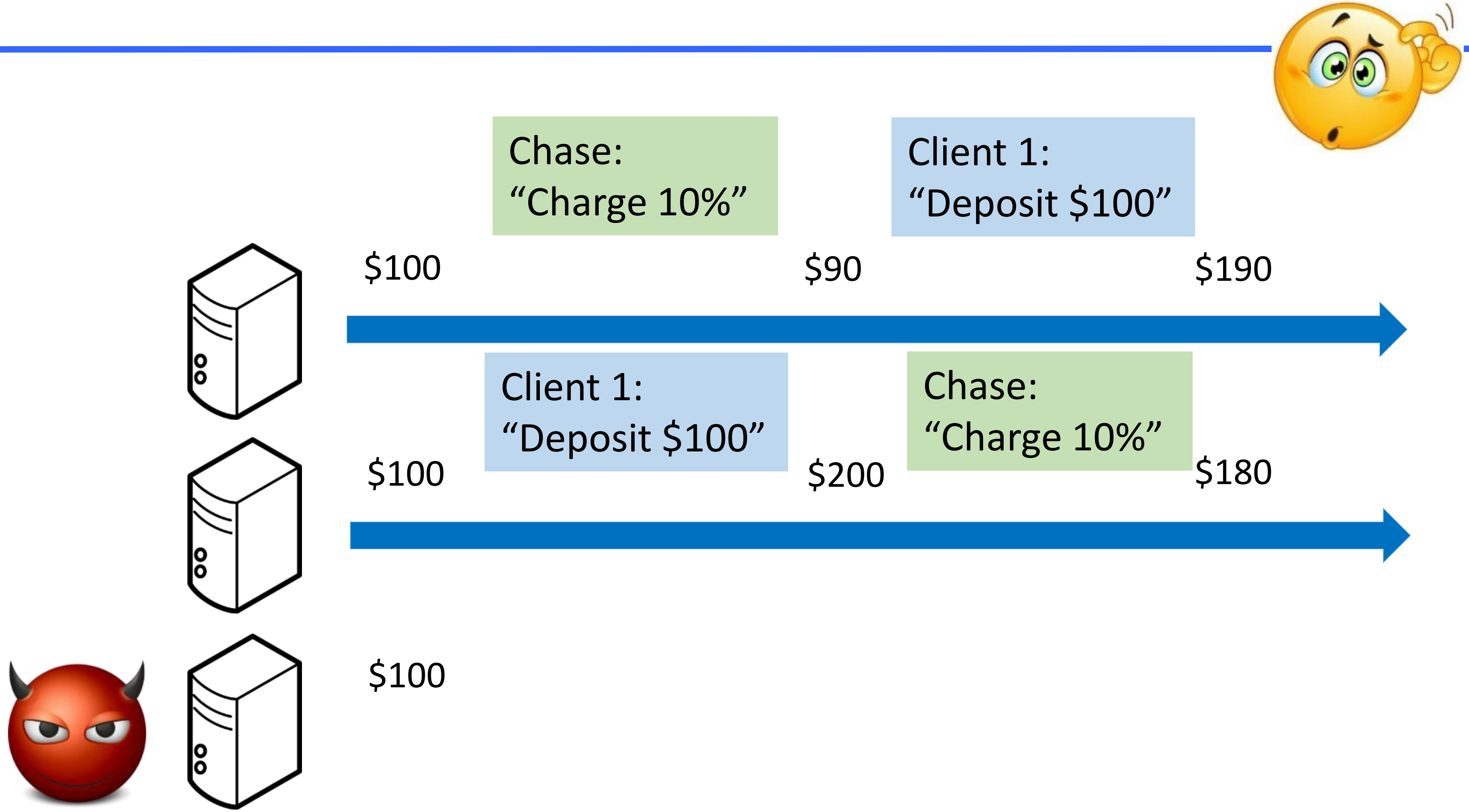
The “Total Order” Requirement



The “Total Order” Requirement

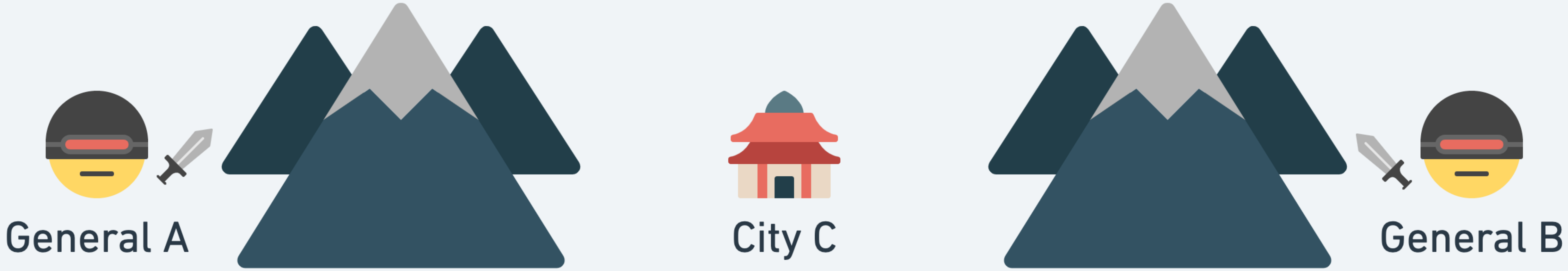


The “Total Order” Requirement

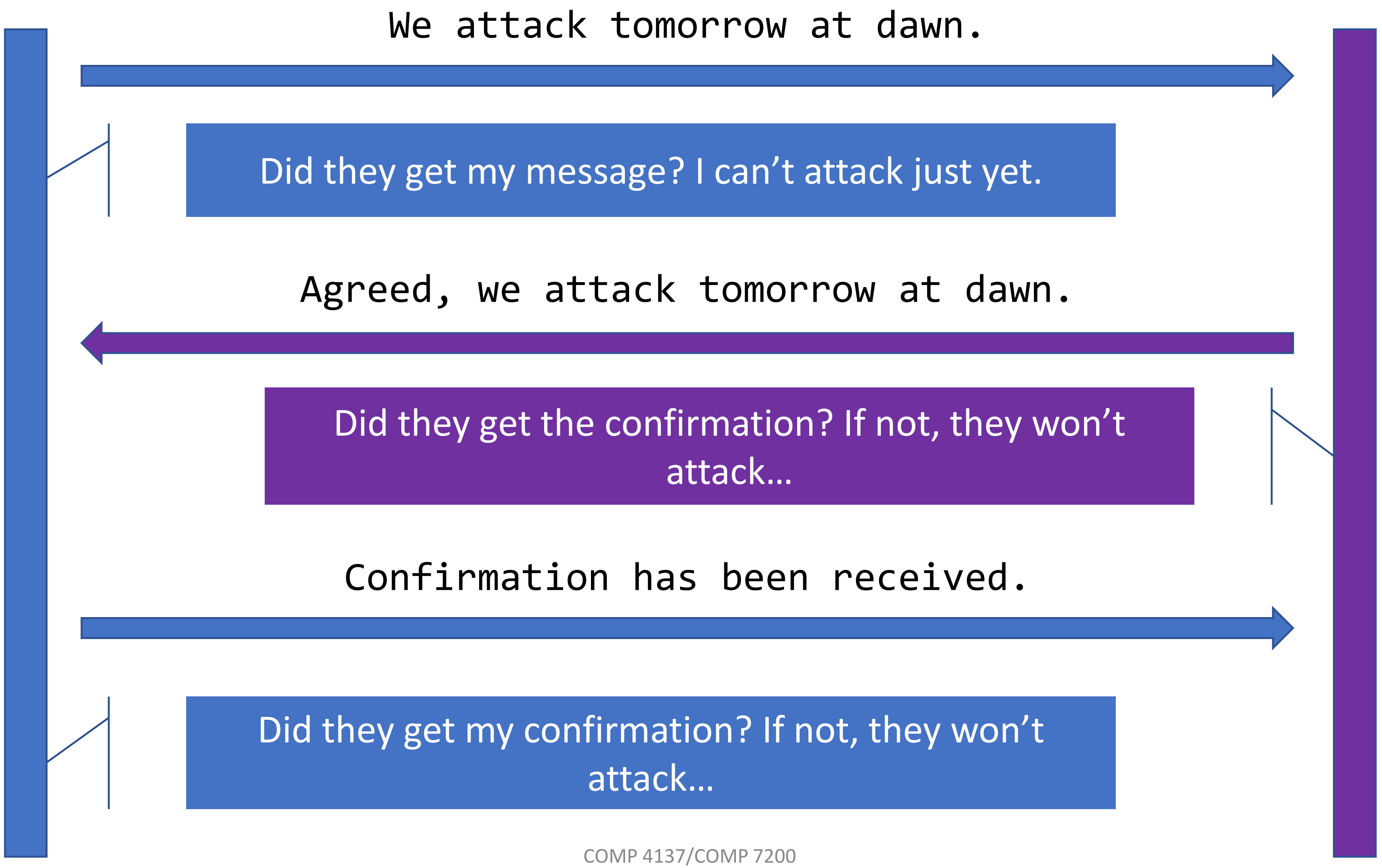


The two generals paradox

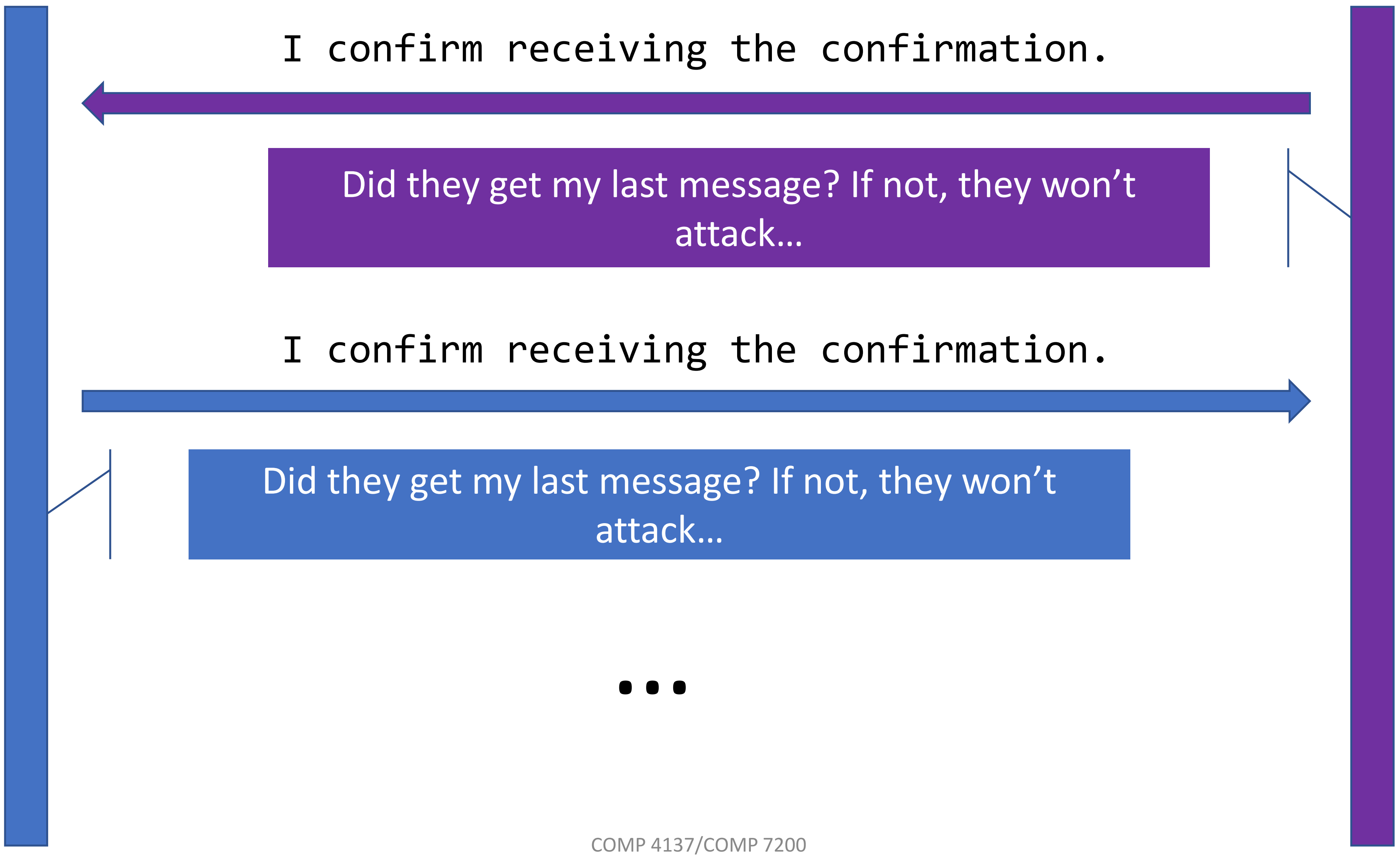
- Two armies have surrounded a city
- Their generals must decide **together** whether to attack or retreat
- Communication through messengers, must pass through the city and might be **intercepted**
- Both must take the **same** decision



Easy enough… or not?



Probably not...



The two generals paradox

- No protocol exists that guarantees both generals are 100% certain of the decision of the other
  - Proofs exist

- After **500 confirmations**, both would be pretty sure the other will attack

- But “pretty sure” is not **guaranteed 100% certainty**

The two generals paradox

Simplified impossibility proof:

- Let's assume a protocol that exchanges **N messages** exists, which guarantees certainty
- The Nth message could be lost… meaning, the first **N-1 messages** *must be sufficient* to guarantee certainty
- Therefore, there exists such a protocol which exchanges **N-1 messages**
- Absurd conclusion: there exists such a protocol that exchanges **0 messages**

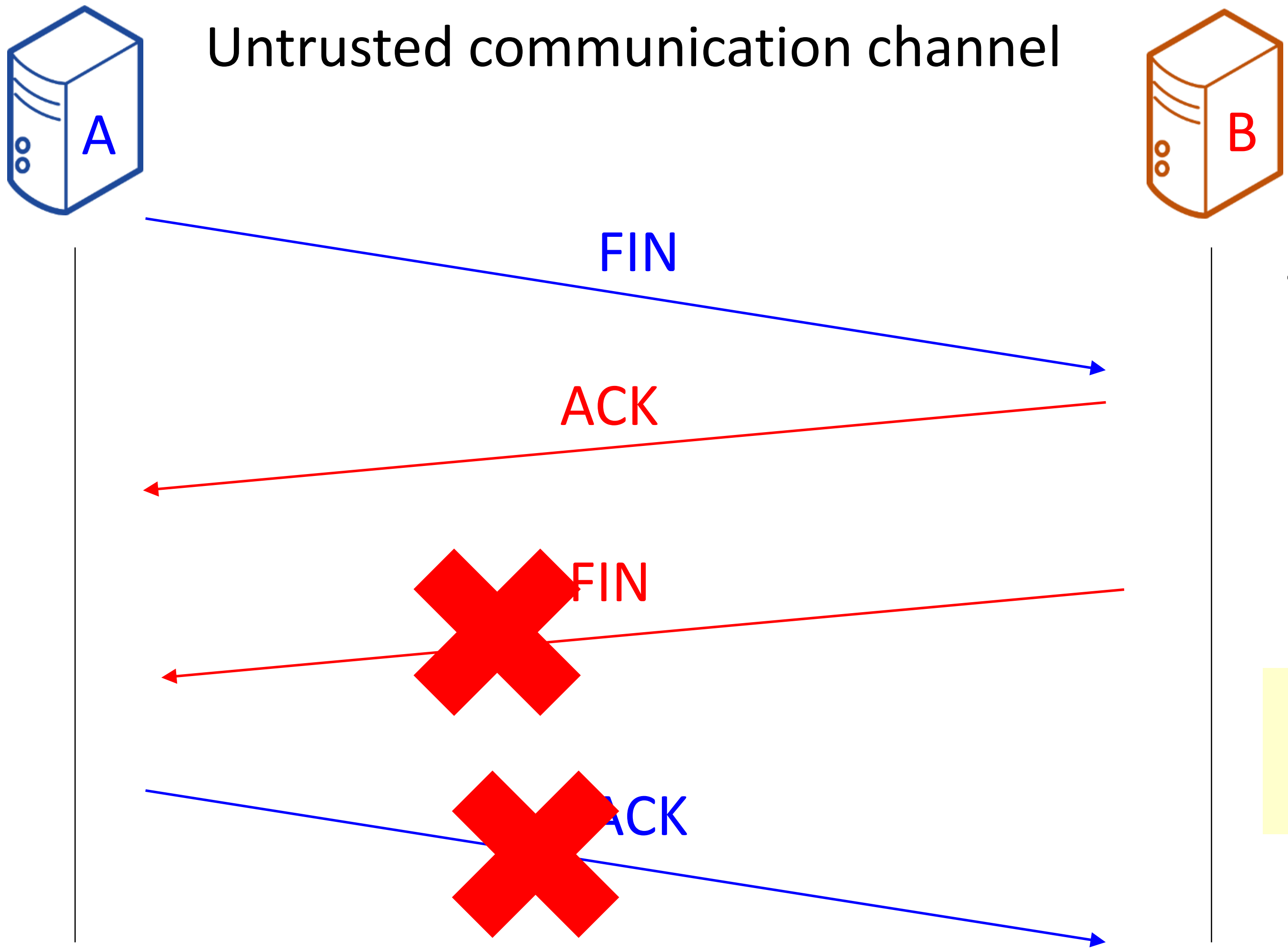
The odd conclusion

- Through an unreliable network, two nodes cannot 100% agree even on a single bit

- **Perfect** state consistency is *<u>not achievable</u>* over unreliable networks – but in practice, that's not required

- Protocols exist that mitigate message delivery uncertainty, typically using retries, ACKs, and timeouts
  - TCP though it does not really solve the problem…

TCP does not solve two generals paradox



This solution leads to a half-open connection.

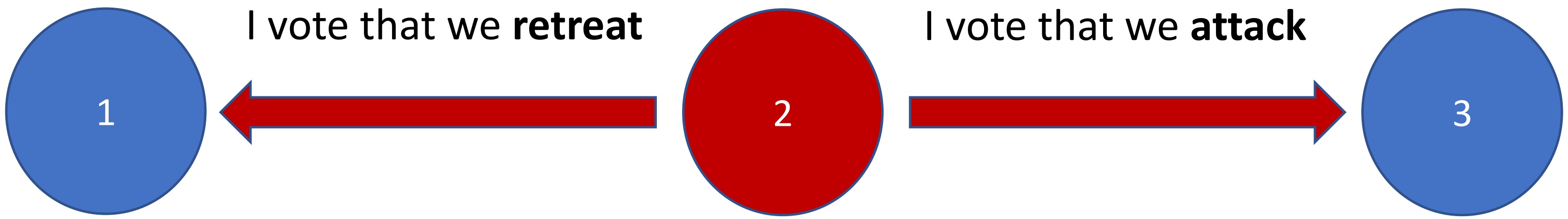
TCP does not solve two generals problem!

The problem of Byzantine Generals

- Generalization of Two Generals
- N generals, decision to attack or retreat based on ***majority vote***
- Some generals might be secretly traitors, and try to ***manipulate*** the vote…
- **Goal:** achieve consensus between honest nodes

The problem of Byzantine Generals

- #1 wants to **attack**
- #3 wants to **retreat**



- #1 receives **retreat** votes from #2 and #3
- #3 receives **attack** votes from #1 and #2

- Result: #3 attacks <u>*alone*</u>, #1 retreats

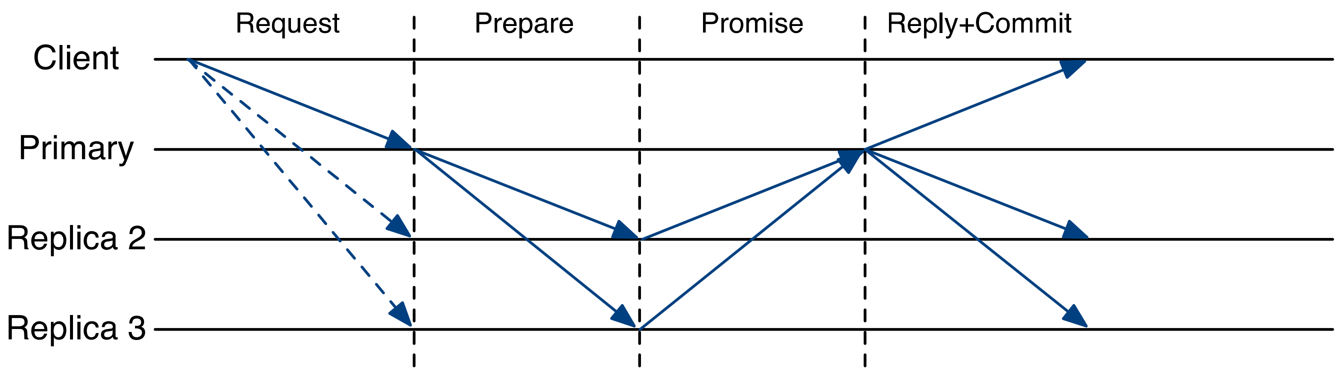
Consensus Algorithms

- **Paxos**
  - Majority rule, asynchronous setting
  - Consistency, fault-tolerance, but may get stuck (2 out of 3 rule) Byzantine-fault intolerance
- **Raft**
  - Leader-Follower model
  - Choose 2 in 3: Safety, Liveness, Fault-Tolerance Byzantine-fault intolerance
  - http://thesecretlivesofdata.com/raft/ (animated example)
- **BFT**
  - Byzantine-fault tolerance

Paxos

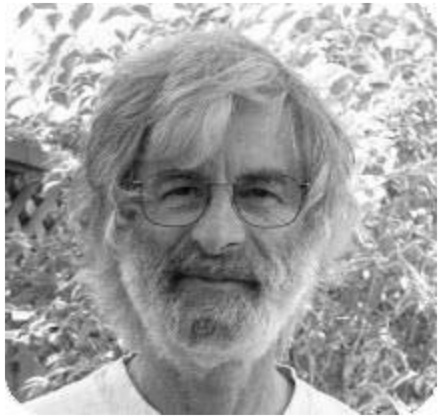
[Lamport, ACM TOCS 1998]; going back to 1989

[Lamport. Paxos made simple. ACM SIGACT News 2001]



"For fundamental contributions to the theory and practice of distributed and concurrent systems, notably the invention of concepts such as causality and logical clocks, safety and liveness, replicated state machines, and sequential consistency."

Turing Award 2013



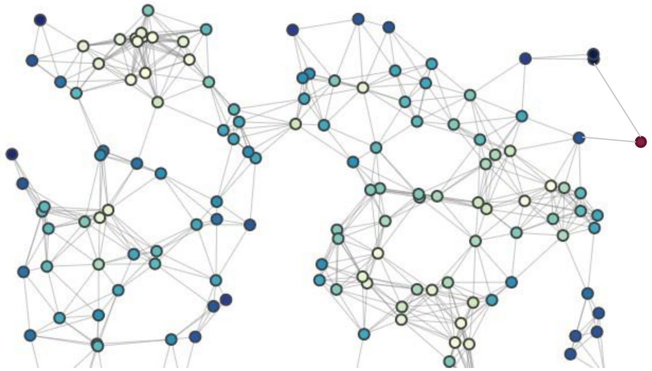
Byzantine Fault-Tolerant SMR (BFT Protocols)

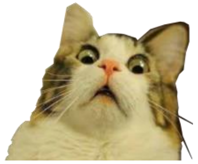
- Traditionally important
  - Powerful: Byzantine/arbitrary failures & attacks
  - Systems, distributed systems, theory, crypto, security, …
- Recently gain prominence
  - Real threats to real systems
  - Blockchains
  - Mission-critical systems (SpaceX)
  - …

Consensus in Public Blockchain

- Traditional consensus works on closed environment
  - Nodes know addresses of their peers Every node accesses a shared memory
- Public blockchain is an open P2P system
  - Where to keep shared memory in P2P?
  - Anyone can join and leave the network at anytime How to enable consensus in an open system?

Signed by Bob
Pay to pk_{Bob}: H ()

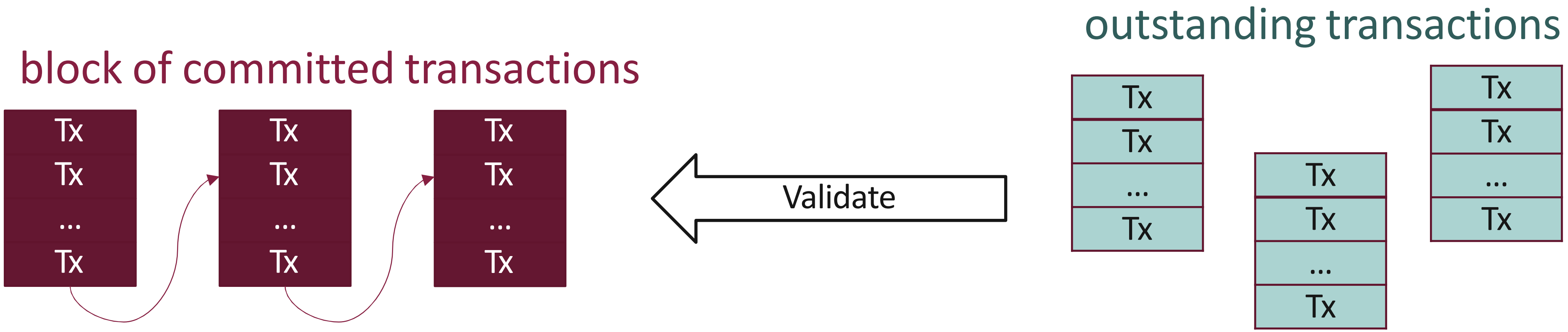




All nodes must agree on the validity of the Bob's transaction

Consensus in Public Blockchain

- *At any given time:*
  - All nodes have a sequence of blocks of transactions
  - they have reached a consensus on (block of committed transactions)
  - Each node has a set of outstanding transactions
  - that need to be validated against block of committed transactions



Block-based consensus

Consensus in Public Blockchain

- Bitcoin introduces <u>incentive</u> concept for honest actions
  - Possible as Bitcoin is a digital currency
- Embrace randomness
  - Does away with the notion of a specific end-point
  - Consensus happens over long-time scales – approx. 1 hour
- Blockchain consensus works better in practice than in theory
  - Theory is catching up
  - Theory is still very important as It can help predict unforeseen attacks