Lecture 10: Fault Tolerance, Group Communication and Replicated State Machines

Thanks to Angela Demke Brown, Sam Toueg and Vassos Hadzilacos

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Basic Concepts & Definitions

- Fault tolerance is the ability of a system to continue operating in the presence of faults
- Closely-related to requirements on dependable systems
  - Availability: probability that system is working correctly at any given time
  - Reliability: probability that system can run continuously without failure
  - Safety: temporary faults do not lead to catastrophic failures
  - Maintainability: ease of repairing a failed system

Avoiding faults

- All of the standard coping with complexity stuff
  - software engineering, testing, etc…
- There are also some design "rules" that can help
  - Example: avoid situations in which things often go wrong
    - 90% utilization of file system capacity
    - minimum number of free pages
  - Example: regular maintenance
    - planned restarts: occasionally reset to clean state
    - patches/upgrades: don't leave known problems laying around
  - Example: detect problematic activity at system boundary
    - firewalls for blocking suspect traffic
- Note that this *reduces* rather than *prevents* problems

Masking/hiding faults

- Obvious requirement: redundancy
  - Must be able to repair broken sets of bits
    - e.g., error correction codes
  - Must be able to handle *transient faults*
    - e.g., resend message, retry disk operations
  - Must be able to communicate despite broken paths
    - e.g., redundant routes, dual ported devices, etc…
  - Must be able to continue with broken servers
    - e.g., have more than one server providing same service
    - Requires *group communication* → distributed consensus

Information redundancy

Time redundancy

Physical redundancy

Recovering from faults

- Many systems are designed to tolerate a single fault
  - Must detect and recover before a second fault occurs
  - Generalizes to tolerating *f* faults, recovering before fault *f+1* occurs
- In general, requires restoring *state* of restarted process or service
  - *Checkpointing:* save state to *stable storage*
  - *Replicated state machines:* rebuild state from other group members

Replicated State Machines (RSMs)

- Architecture
  - Implement a service as a state machine
    - State variables
    - Commands
  - Replicate the state machine on different servers
  - Clients interact with sets of servers
- Rationale
  - Fault-tolerance / Availability / Reliability

State Machine Commands

- A message that the state machine receives
- Commands must execute atomically with respect to other commands
  - Referred to as 'linearizability'
- Commands
  - Modify state variables
  - Produce outputs
- The state/output of a state machine is completely determined by:
  - Initial state
  - Sequence of commands

RSMs & Failures

- In the case of failures
  - Clients must determine correct output of RSMs
  - RSMs are called t-tolerant
    - Fail-stop: t + 1 replicas required (1 correct replica sufficient)
    - Byzantine: 2t + 1 replicas required (t + 1 correct replicas sufficient)
- Different than Broadcast/Consensus context. Why?
  - One client must decide on result, replicas don't have to agree with each other about result

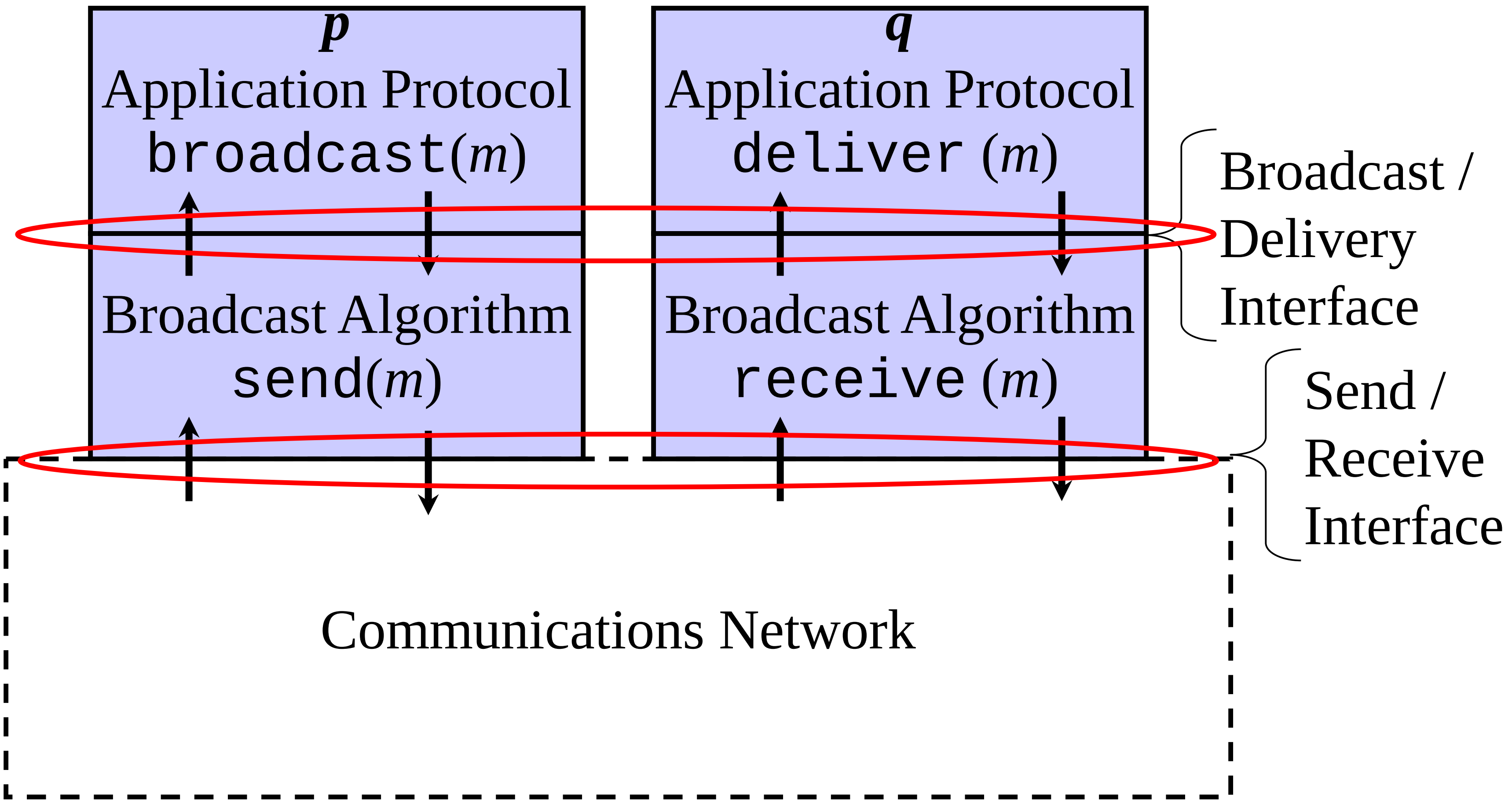
RSMs, Consensus & Reliable Broadcast

- Each correct replica
  - Must receive every request (“Agreement” requirement)
  - Must execute same commands in same order (“Order” requirement”)
  - Since all correct replicas must have the same state!
  - Therefore, RSMs require Distributed Consensus to agree on the order of commands
- Needs form of group communication called atomic broadcast

Group communication

- In many applications processes must be able to reliably broadcast messages, so that they agree on the set of messages they deliver.
- Difficulty: distributed processes do not know each other's state.
- Much of this material is based on Chapter 5 by Hadzilacos and Toueg in "Distributed Systems", Sape Mullender, ed.
  - Reliable broadcast taxonomy
  - Example broadcast algorithms

Application / Broadcast Mechanism



Properties of `Send/Receive`

- Validity: If p sends m to q, and both p and q and the link between them are correct, then q eventually receives m.

Liveness

- Uniform Integrity: For any message m, q receives m at most once from p, and only if p previously sent m to q.

Safety

- E.g. Communication with TCP

Properties of `Broadcast/Deliver`

- Reliable Broadcast satisfies the following properties:
- Validity: If a correct process broadcasts a message m, then all correct processes eventually deliver m.

Liveness

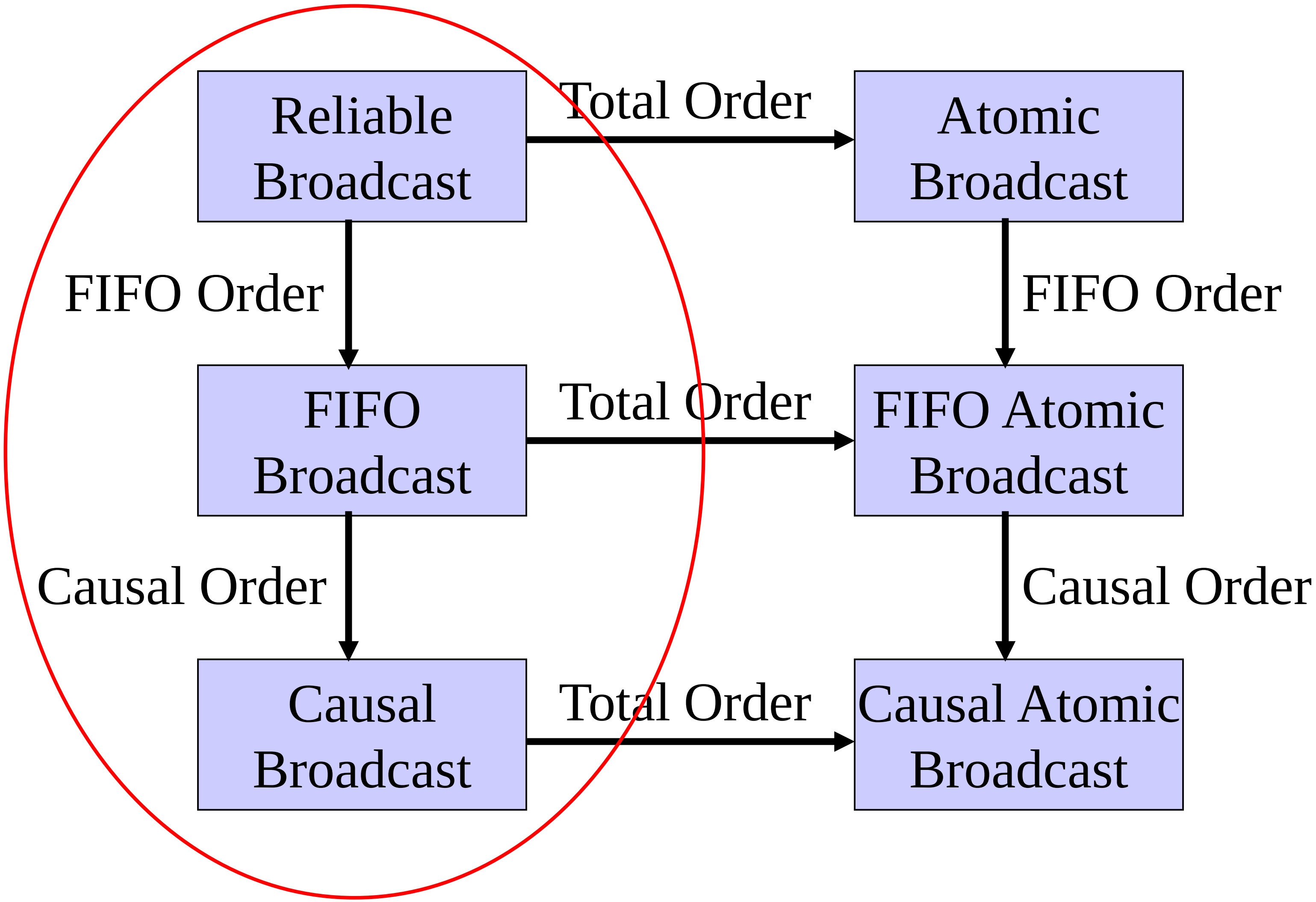
- Agreement: If a correct process delivers a message m, then all correct processes eventually deliver m.
- Integrity: For any message m, every correct process delivers m at most once, and only if m was previously broadcast by sender(m).

Safety

Message Order

- *Unordered:* no guarantees on delivery order
- *FIFO Order*: If a process broadcasts a message *m* before it broadcasts a message *m'*, then no correct process delivers *m'* unless it has previously delivered *m*.
- *Causal Order*: If the broadcast of a message *m* causally precedes the broadcast of a message *m'*, then no correct process delivers *m'* unless it has previously delivered *m*.
- *Total Order*: All correct processes deliver messages in the same order
  - Basically, every process sees messages in the exact same order
  - Total Order does not imply either FIFO or Causal, just the same order for everyone!
  - May be combined with any of the above delivery constraints (No Order, FIFO or Causal)

Broadcast Taxonomy



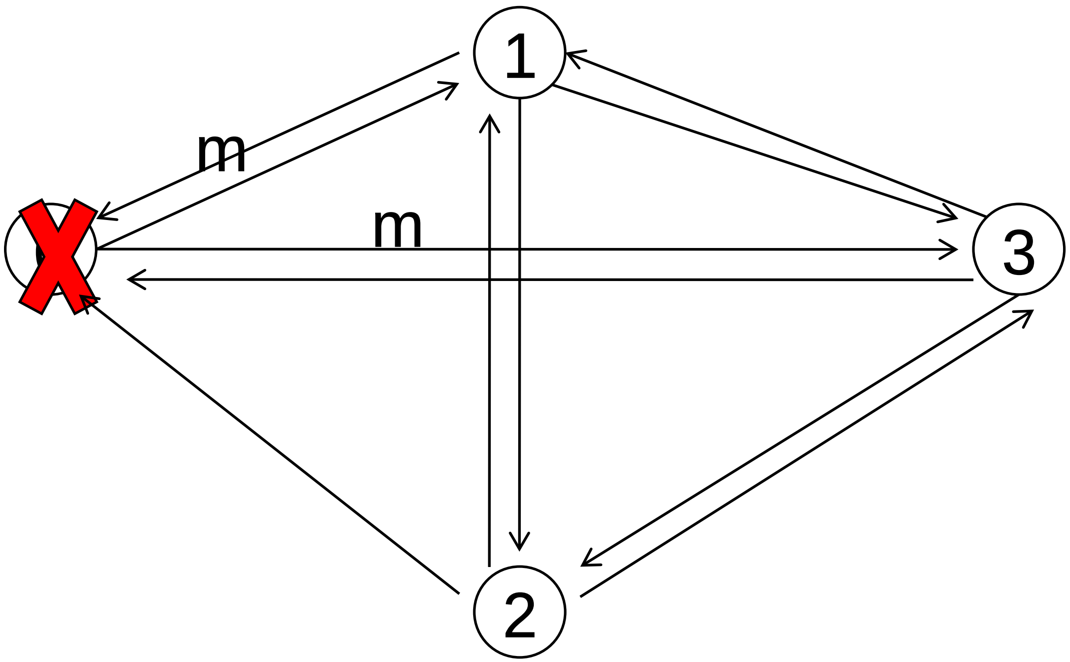
Reliable Broadcast Alg. (Diffusion)

Every process *p* executes:

```
//to reliably broadcast messages
ReliableBroadcast(m):
   //make m unique
   tag m with sender(m), sequence_number(m)
   send(m) to all neighbors including p
```

```
//event loop for receive events
   upon receive(m) do
       if p has not previously executed ReliableDeliver(m)
       then
             if sender(m) ≠ p
             then
                   send(m) to all neighbors
             ReliableDeliver(m)
```

Diffusion Algorithm Illustrated



- All correct processes take on role of broadcaster upon receipt of message

“Diffusion” Algorithm Considered

- Works in synchronous or asynchronous system
- Assumes network does not partition
- Failures assumed to be fail-stop
- Floods the network
    - especially if processes are highly connected

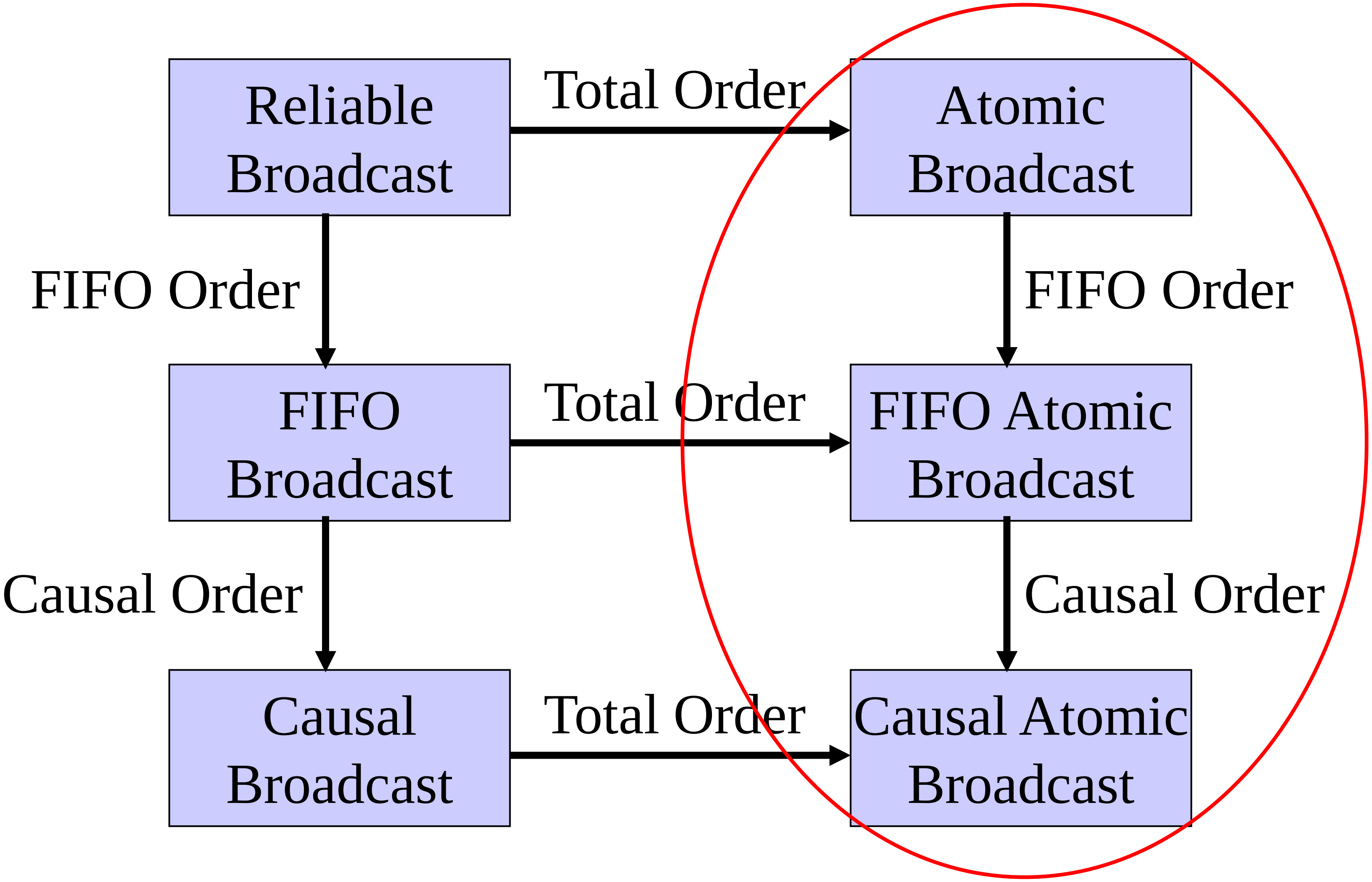
FIFO Broadcast Algorithm

- FIFO Algorithm is layered on top of Reliable Broadcast
- Each process *p* sends a message *m* to its neighbors, and tags it with p's sender# and a sequence#.
- Each process *p* maintains, for each other process q_i, the next sequence number it can **`FIFODeliver`**
- Buffers **`ReliableDeliver'`**ed messages until the sequence number indicates message may be **`FIFODeliver'`**ed

Causal Broadcast Algorithm

- Causal algorithm is layered on top of FIFO alg.
- **`CausalBroadcast`** prepends list of messages upon which *m* causally depends then calls **`FIFOBroadcast`**
- Dependent messages is the list of messages **`CausalDeliver'`**ed since last **`CausalBroadcast`**.
- Buffers **`FIFODeliver'`**ed messages until all messages upon which *m* depends have been **`CausalDeliver'`**ed.

Broadcast Taxonomy



Atomic Broadcast

- How do we enforce total ordering?
  - FIFO: sequence numbers, Causal: dependencies sent with m
  - What happens if all (even unrelated) messages should be seen in the same order?

=> Atomic Broadcast is a form of Distributed Consensus

  - Therefore no deterministic, asynchronous algorithm
  - Synchronous algorithms for various failure models exist

- Other Atomic Broadcast algorithms can be built on top of Atomic Broadcast with similar limitations
  - FIFO Atomic Broadcast
  - Causal Atomic Broadcast

Schneider Tutorial on RSMs

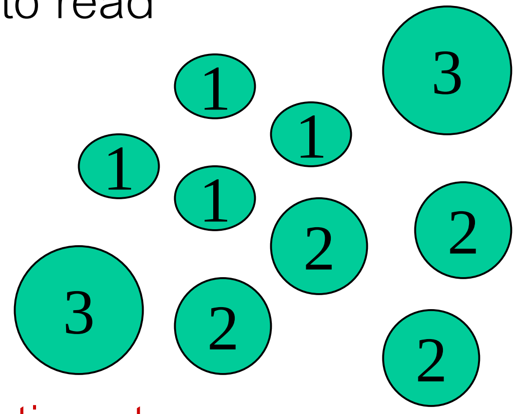
- Not distinguished for clarity of assumptions/model of failure and synchrony
  - But better than any other paper as an introduction to RSMs
- Ties together:
  - Broadcast, consensus,
  - logical clocks, clock synchronization
  - leases, heart beats, failure detectors,
  - group membership (reconfiguration),
  - recovery (managing configuration)

Another Viewpoint/Approach

- So far:
- Distributed Consensus
  - Servers communicate amongst themselves to reach agreement on state.
- Reliable Broadcast
  - Servers communicate amongst themselves to order messages
- What can clients do?
  - Clients can read and write to sets of servers in a consistent manner
  - Storing/restoring the state variables to servers & implementing a state machine locally is similar to RSMs

Voting

- Let V be the number of votes in the system
- Let W be the number of votes required to write
- Let R be the number of votes required to read
- Overlap Constraint (Requirement):
  - 1. $V < R + W$
- Recommended:
  - 2. $V < 2 * W$
- Data must contain a version number or timestamp
- If version numbers used => 2. becomes a requirement!
- If constraints are met, then data will remain consistent.
- Note that votes can be arbitrarily assigned to servers in the system (i.e. weights can be assigned to servers)



$V=18$
$W=12$
$R=7$

D. Gifford, "Weighted Voting for Replicated Data" SOSP 1979

Selecting size of R and W

- Consider the case of 3 replicas
- Three possible choices
  - R=3, W=1 (Read all, write any)
    - Fast writes at expense of reads
    - Single failure may lose most recent data
  - R=1, W=3 (Read 1, write all)
    - Fast reads at expense of writes
    - Single failure makes it impossible to write new data
  - R=2, W=2
    - Good tradeoff

Next Time

- More on replicated state machine approach
- Some recent examples
  - Apache Zookeeper
  - Raft consensus algorithm