

Lecture 20: Fault Tolerance, Group Communication and Replicated State Machines

CSC 469H1F
Fall 2006
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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



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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



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Masking/hiding faults

- Obvious requirement: redundancy
 - Must be able to repair broken sets of bits
 - e.g., error correction codes
 - 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



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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

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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

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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

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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 (t correct replica sufficient)
 - Byzantine: $2t + 1$ replicas required ($t + 1$ correct replicas sufficient)
- Different than Broadcast/Consensus failures
 - One client must decide on result, replicas don't have to agree

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RSMs, Consensus & Reliable Broadcast

- Each correct replica
 - Must execute same commands in same order
 - Since all correct replicas must have the same state
 - Therefore, RSMs require Distributed Consensus to agree on order of commands
- Needs form of *group communication* called *atomic broadcast*

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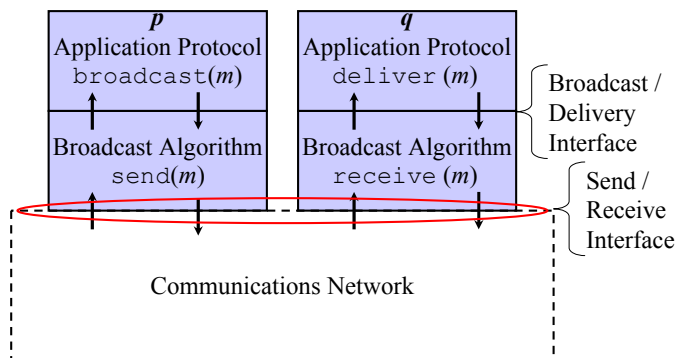
Group communication

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

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Application / Broadcast Mechanism



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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 .
- *Uniform Integrity*. For any message m , q receives m at most once from p , and only if p previously sent m to q .
- E.g. Communication with TCP

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Properties of Broadcast/Deliver

- *Validity*: If a correct process broadcasts a message m , then all correct processes eventually deliver m .
- *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 $sender(m)$.

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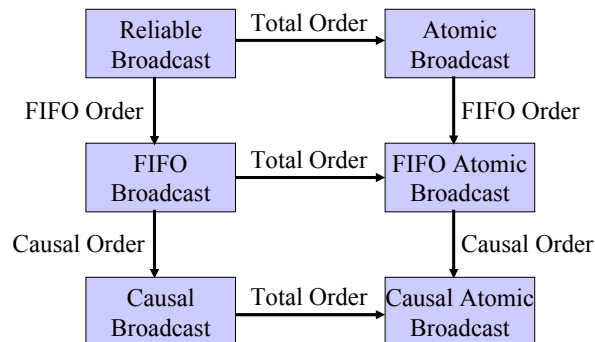
Message Order

- *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
 - May be combined with any of the above delivery constraints

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Broadcast Taxonomy



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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  $sender(m) \neq p$ 
        then
            send( $m$ ) to all neighbors
    ReliableDeliver( $m$ )
  
```

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"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

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FIFO Broadcast Algorithm

- FIFO Algorithm is layered on top of Reliable Broadcast
- Each process p maintains, for each other process q_i , the next sequence number it can **FIFO**Deliver
- Buffers **Reliable**Delivered messages until the sequence number indicates message may be **FIFO**Delivered

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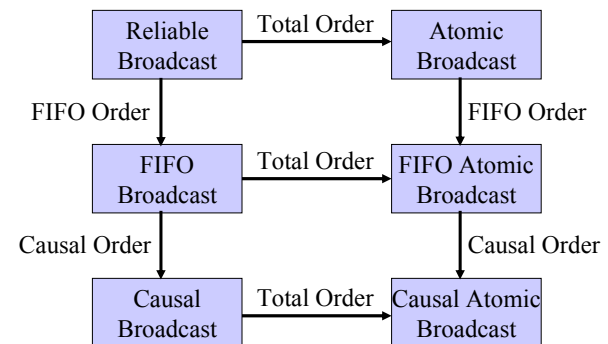
Causal Broadcast Algorithm

- 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 **CausalDelivered** since last **CausalBroadcast**.
- Buffers **FIFO**Delivered messages until all messages upon which m depends have been **CausalDelivered**.

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Broadcast Taxonomy



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Atomic Broadcast

- Atomic Broadcast is 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

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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)

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Another Viewpoint/Approach

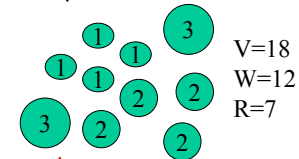
- Distributed Consensus
 - Servers communicate amongst themselves to reach agreement on state.
- Reliable Broadcast
 - Servers communicate amongst themselves to order messages
- What can clients do?
 - Clients can read and write to sets of servers in a consistent manner
 - Storing/restoring the state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

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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:
 - $R + W > V$
- Recommend:
 - $2 \cdot W > V$
 - $R + W < V + \epsilon$
- **Data must contain a version number**
- 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)



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Quorums

- Quorums are a generalization of voting.

- Organize servers into logical structures.

- Overlap constraint

- Every write quorum must overlap with every read quorum

- Example: writes must go to a column, reads must get a row.

- Note that voting **does not imply majority**

