Fault Tolerance

CS239
Advanced Operating Systems

November 28, 2000
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Lecture Source Materials

Singhal, Ch. 13: **Fault Tolerance**

IEEE Computer, April, 1997

Sources of Failure in the PSTN, p. 31-6
(also http://hissa.nist.gov/kuhn/pstn.html)
Understanding FT & Reliability, p. 45-50
Beyond Fault Tolerance, p. 47-49
Toward Systematic Design of FT Systems, p. 51-8
Software-based Replication for FT, p. 68-74

Additional Source Materials

- papers by Jim Gray
  - Why do computers stop and what can be done about it?, August, 1986. (5th SRDSDS)
  - High-Availability Computer Systems, September, 1991. (IEEE Computer)

Outline

- Introduction
- Atomicity and Commit/Abort
- Commit Protocols
- Voting Protocols
- Failure-resilient Processes
- Reliable Communication
- Summary

Prologue

- Failure causes, revisited
  - Gray's 1985 paper says people are the problem
  - Kuhn's 1997 paper says people are the problem and says human intervention is key to reliability

Introduction

- Failure recovery takes time, is disruptive.
- Fault tolerant systems either
  - mask failures
  - exhibit well-defined failure behavior
- Redundancy
  - processes
  - hardware
  - data

Failure implications

- Process deaths
  - reclaim resources
  - unblock waiting clients/release server
- Machine failure
  - sometimes indistinguishable from process death
- Network failure
  - network partitions
  - machine/network failure often indistinguishable

Atomicity and Commit/Abort

- Atomicity
  - indivisible, instantaneous, non-interruptable

Process P1	Process P2
----	----
Lock (x);	Lock (x);
x := x + y;	x := x + z;
Unlock(x);	Unlock(x);
----	----
failure	

Atomic action

- extends machine instruction atomicity to
  - sequence of instructions
  - group of processes
- basic building block of FT operations
- what are characteristics of atomic action?

Action is atomic if...

- process performing action is unaware of other processes, and vice versa
- process performing action doesn't talk to other processes while performing action
- process can't detect other state changes, and hides own state changes until completion
- action is considered by all other processes to be indivisible, instantaneous

Transaction

- Transaction
  - groups sequence of actions
  - group is treated as atomic action
  - decides at some point to commit or abort
- Commit: unconditional guarantee that transaction will complete (permanent)
- Abort: unconditional guarantee that none of transaction pieces will persist

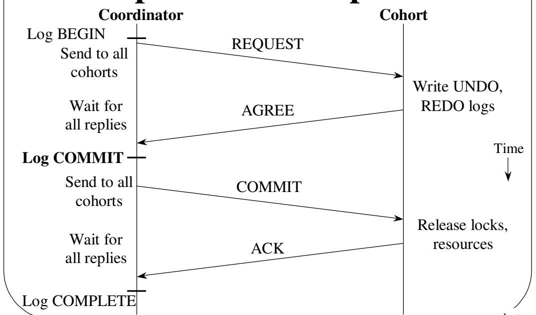
Global atomicity

- atomic action spread over multiple players
- enforced by Commit Protocols
  - used with local recovery strategies
  - "well defined failure behavior" FT class

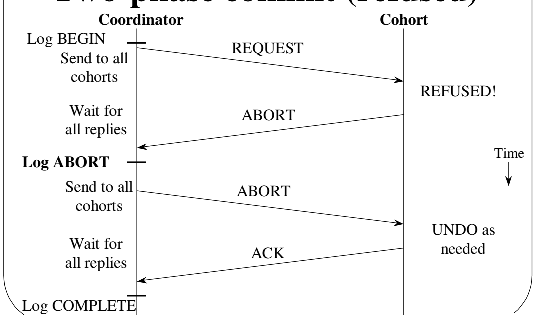
Commit Protocols

- Blocking
  – Two-phase commit
- Nonblocking
  – Three-phase commit

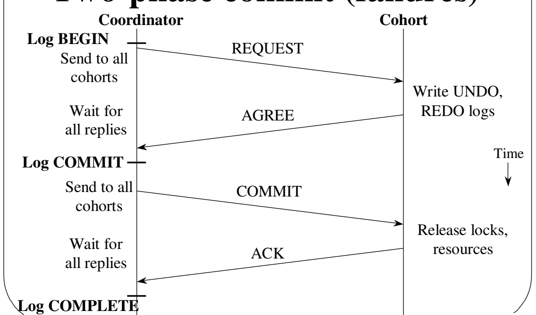
Two-phase commit protocol



Two-phase commit (refused)



Two-phase commit (failures)



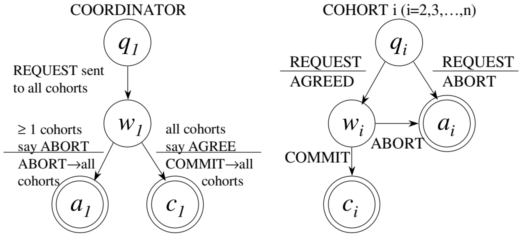
Nonblocking Commit Protocols

- If 2PC coordinator fails, cohorts blocked until recovery of coordinator
  – cohorts may hold locks for long time
  – 2PC not very resilient to site failures
- Blocking avoidable if sites can self-recover
- Communications assumptions
  – reliable network; point-to-point guaranteed
  – site failure detectable/reportable by network (!)

Synchronous protocols

- Must find out why 2PC can't self-recover
- Use finite state machines to model protocol
- Focus on "synchronous within 1 transition"

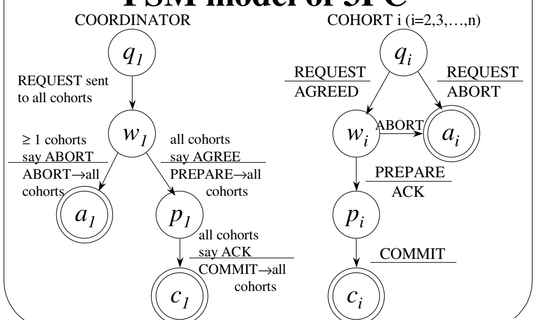
FSM model of 2PC



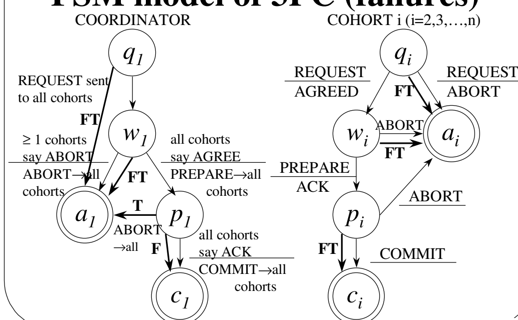
Synchronous protocols, cont.

- *Concurrency set* for each site/state
  - 2PC has concurrency sets with commit/abort
  - a protocol which avoids concurrency sets with both commit and abort allows independent recovery of a single failed site

FSM model of 3PC



FSM model of 3PC (failures)



Independent Recovery notes

- 3PC protocol is for single-site failure IR
- Multi-site failure IR is proven impossible
- Nonblocking protocol impossible when
  - network partition with lost messages
  - multiple network partitions
- Conclusions
  - 3PC good for common case (single failure)
  - expensive in rounds, messages vs. 2PC

Voting Protocols

- Mask failures in a system, especially >1
- Voting tolerates
  - network partitions, site failures, lost messages
- Static
- Dynamic
  - Majority-based
  - Vote reassignment

Static Voting

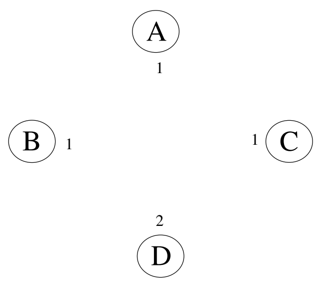
- System model
  - – one replica per site
  - – file access requires lock grant
    - single writer, no readers
    - multiple readers, no writers
  - – each replica has version number
    - monotonically increasing
    - atomically incremented with replica update
    - kept on stable storage

Static Voting, cont.

- Basic idea
  - – each replica is assigned a set number of votes
  - – read or write permitted if requesting process collects proper number of votes
    - total votes v
    - read quorum r
    - write quorum w
    - $r + w > v$
    - $w > v/2$

Static voting example

$v = 5$
$w = 3$
$r = 3$



Static voting, cont.

- Vote assignment properties
  - – write quorum prevents simultaneous writes in distinct partitions
  - – nonnull intersection of all read/write quorums → current copy available in read quorum
  - – no obsolete copy chosen for write update
  - – always current subset whose votes sum to w

Static voting protocol

- Initiator asks local lock manager for lock
  - – on grant, send Vote_Req to all replicas
- Receiver asks local lock manager for lock
  - – on grant, send <version number,votes> back
- Initiator decides if quorum achieved
  - – if read, and sum of votes ≥ r, have quorum
  - – if write, and sum of votes ≥ w, have quorum

Static voting protocol, cont.

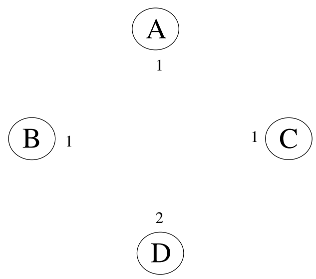
- If initiator fails to achieve quorum
  - – send Release_lock to all paticipants (+ self)
- If initiator achieved quorum
  - – ensure local replica is current
  - – use local copy for read/write request
  - – if write
    - update version number
    - transmit new version number, version to all
  - – release all locks, both local and remote

Static voting flexibility

$v = 5$
$w = 3$
$r = 3$

$v = 5$
$w = 4$
$r = 2$

$v = 5$
$w = 5$
$r = 1$



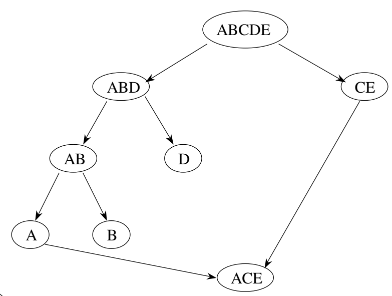
Dynamic Voting

- Motivation
  - multiple failures may prevent getting quorums
  - dynamic protocols adapt to system state
    - adjust quorum size, vote assignment
- Majority-based
- Vote reassignment

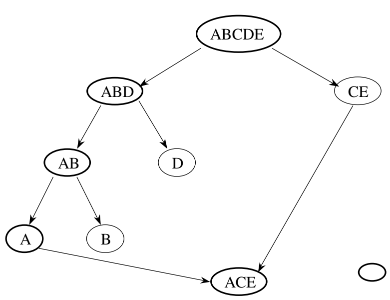
Majority-based dynamic voting

- Adjust set of sites forming majority
  - from operable communicating current replicas
- Partition graph represents network history
- Use history to determine new quorum
  - based on previous quorum

Partition graph



Majority concept

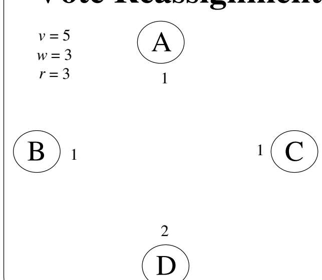


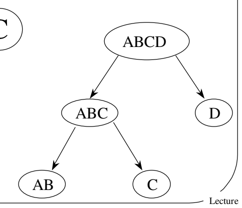
Assume 1 vote per replica

Distinguished partition

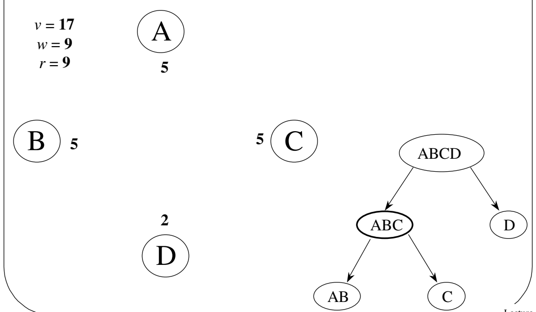
Vote Reassignment Motivation

$v = 5$
$w = 3$
$r = 3$





Dynamic Vote Reassignment



Dynamic Vote Reassignment

- Group consensus
  - majority group sites run agreement protocol
  - yields high quality vote assignment
- Autonomous reassignment
  - majority group members individually select new votes for self
  - then, get approval from majority
  - complex version vector-based protocol
  - possibly quicker than group consensus

Failure-resilient Processes

- Minimal disruption of service provided by process in event of system failure
  - resilient process masks failures and guarantees progress despite set number of system failures
- Backup processes
- Replicated execution

Backup processes

- Primary, backup processes
- Checkpoint from primary to backup
- Few system resources for inactive backup
- Delays during checkpointing
- Delay after failure
  - detect failure
  - backup recomputation from checkpoint onward
- Multiple backups must select primary

Replicated Execution

- Concurrent execution
- Can increase reliability, availability
  - reliability: majority consensus among results
  - availibility: use any result
- Main cost is multiple CPU investment
- Nonidempotent operations (random, I/O)
- Message ordering problems among copies
- Communications with "outside world"

Reliable Communication

- Assume replicated data, per site manager
- To update, process sends identical messages
- Suppose process fails after sending
  - Manager gets updates, then learns of failure
  - Manager learns of failure, then gets update
  - Manager neither gets updates nor learns failure
- How to get identical manager behavior?

Reliable communication, cont.

- If two conditions met, have identical view
  - messages received are identically ordered
  - all/none message delivery
- Atomic broadcast
  - Two-phase protocol

Atomic Broadcast

- Phase one
  - sender multicasts message
  - receiver buffers message; replies with priority
- Phase two
  - sender chooses highest priority from receivers
  - sender multicasts priority
  - receiver assigns priority; adds message to delivery queue in priority order
- Receiver-initiated recovery protocol

Summary

- Fault tolerance prevents disrupted service
  - well-defined failure behavior
  - mask failure
- Commit protocols
  - blocking/nonblocking
- Voting protocols
  - static/dynamic
- Resilient processes, communication