Atomic Commit

The objective

Preserve data consistency for distributed transactions in the presence of failures

But what is a transaction?

Motivating example

```
UPDATE Budget
SET money=money-100
WHERE pid = 1

UPDATE Budget
SET money=money+60
WHERE pid = 2

UPDATE Budget
SET money=money+40
WHERE pid = 3
```

Motivating example

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SELECT sum(money)
FROM Budget
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```
SELECT sum(money)
FROM Budget
```

Would like to treat each group of instructions as a unit

Transaction definition

- **A transaction** = one or more operations that correspond to a single real-world transition
- Examples
  - Transfer money between accounts
  - Purchase a group of products
  - Register for a class (either wait list or allocated)

ACID properties

- Atomicity: Either all changes performed by transaction occur or none occurs
- Consistency: A transaction as a whole does not violate integrity constraints
- Isolation: Transactions appear to execute one after the other in sequence
- Durability: If a transaction commits, its changes will survive failures

- Goal: maintain these four properties in spite of failures and concurrency

Transaction example

```
START TRANSACTION
UPDATE Budget SET money = money - 100
WHERE pid = 1
UPDATE Budget SET money = money + 60
WHERE pid = 2
UPDATE Budget SET money = money + 40
WHERE pid = 3
COMMIT
```

Rollback

- If the app gets to a place where it can't complete the transaction successfully, it can execute a **ROLLBACK**
- This causes the system to "abort" the transaction
  - Database returns to a state without any of the changes made by the transaction

Reasons for rollback

- User changes his or her mind ("ctl-C"/cancel)
- Explicit in program, when app program finds a problem
  - e.g. when quantity on hand < quantity being sold
- System-initiated abort
  - System crash
  - Deadlocks

Transaction significance

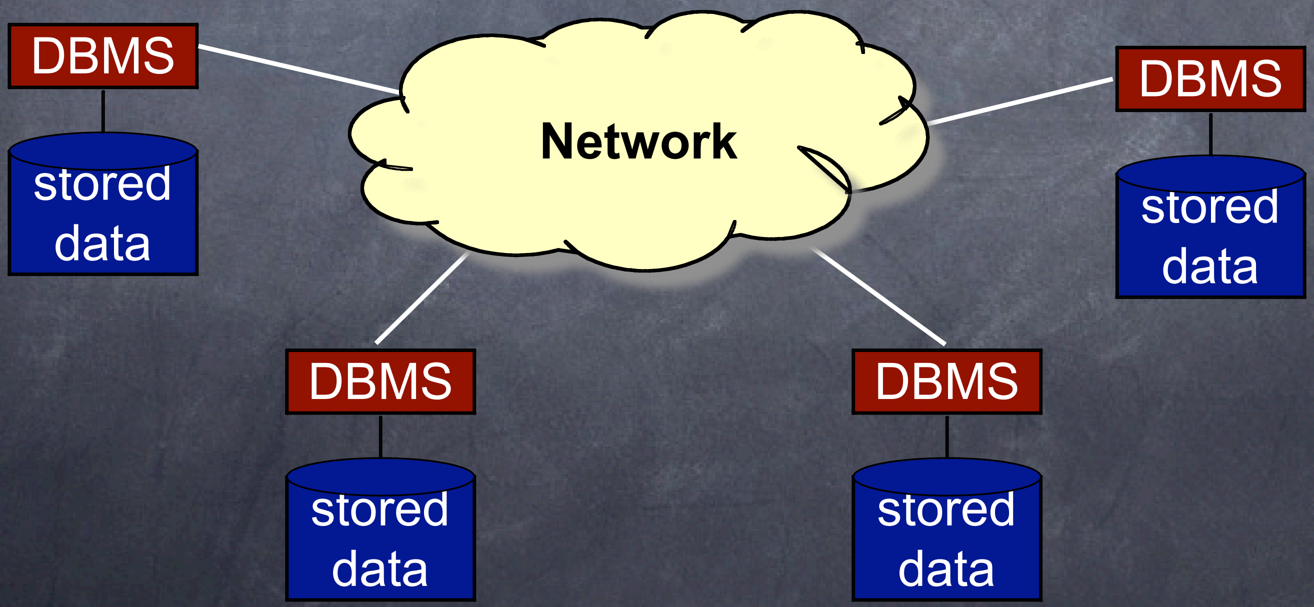
- Major component of database systems
- Critical for most applications

- Turing awards to database researchers:
  - Charles Bachman 1973
  - Edgar Codd 1981 for inventing relational dbs
  - Jim Gray 1998 for inventing transactions

So what do transactions have to do with distributed systems?

Distributed database management system

- Important: many forms and definitions
- Our definition: shared nothing infrastructure
  - Multiple machines connected with a network



Distributed transactions

- In a distributed DBMS, transactions may span multiple sites
  - A transaction may need to update data items located at different sites
  - All operations must be performed as a unit (with ACID properties)
- Important goal: ensure atomic commit of all distributed transactions

Model

- For each distributed transaction T:
  - one coordinator
  - a set of participants
- Coordinator knows participants; participants don't necessarily know each other
- Each process has access to a Distributed Transaction Log (DT Log) on stable storage

The setup

- Each process p_i has an input value $vote_i$:

$$vote_i \in \{\text{Yes, No}\}$$

- Each process p_i has output value $decision_i$:

$$decision_i \in \{\text{Commit, Abort}\}$$

AC Specification

AC-1: All processes that reach a decision reach the same one.

AC-2: A process cannot reverse its decision after it has reached one.

AC-3: The Commit decision can only be reached if all processes vote Yes.

AC-4: If there are no failures and all processes vote Yes, then the decision will be Commit.

AC-5: If all failures are repaired and there are no more failures, then all processes will eventually decide.

Comments

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AC1:

- We do not require all processes to reach a decision
- We do not even require all correct processes to reach a decision (impossible to accomplish if links fail)

AC4:

- Avoids triviality
- Allows Abort even if all processes have voted yes

NOTE:

- A process that does not vote Yes can unilaterally abort

Liveness & Uncertainty

- A process is uncertain when
  - It has already voted Yes
  - But it does not yet have sufficient information to know the global decision
- While uncertain, a process cannot decide unilaterally
- Uncertainty + communication failures = blocking!

Liveness & Independent Recovery

- Suppose process p fails while running AC.
- If, during recovery, p can reach a decision without communicating with other processes, we say that p can independently recover
- Total failure (i.e. all processes fail) - independent recovery = blocking

A few character-building facts

Proposition 1

If communication failures or total failures are possible, then every AC protocol may cause processes to become blocked

Proposition 2

No AC protocol can guarantee independent recovery of failed processes

2-Phase Commit

Coordinator c

Participant p_i

I. sends VOTE-REQ to all participants

2-Phase Commit

Coordinator c

Participant p_i

I. sends VOTE-REQ to all participants

II. sends $vote_i$ to Coordinator

if $vote_i$ = NO then

$decide_i$:= ABORT

halt

2-Phase Commit

Coordinator c

I. sends VOTE-REQ to all participants

Participant p_i

II. sends $vote_i$ to Coordinator
   if $vote_i$ = NO then
      $decide_i$:= ABORT
      halt

III. if (all votes YES) then
   $decide_c$:= COMMIT
   send COMMIT to all
else
   $decide_c$:= ABORT
   send ABORT to all who voted YES
halt

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Notes on 2PC

- Satisfies AC-1 to AC-4
- But not AC-5 (at least "as is")
  i. A process may be waiting for a message that may never arrive
     - Use Timeout Actions

  ii. No guarantee that a recovered process will reach a decision consistent with that of other processes
     - Processes save protocol state in DT-Log

Timeout actions

Processes are waiting on steps 2, 3, and 4

Step 2 p_i is waiting for VOTE-REQ from coordinator

Step 3 Coordinator is waiting for vote from participants

Step 4 p_i (who voted YES) is waiting for COMMIT or ABORT

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Coordinator can decide ABORT, send ABORT to all participants which voted YES, and halt.

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p_i cannot decide: it must run a termination protocol

Termination protocols

I. Wait for coordinator to recover
   - It always works, since the coordinator is never uncertain
   - may block recovering process unnecessarily

II. Ask other participants

Cooperative Termination

- c appends list of participants to VOTE-REQ
- when an uncertain process p times out, it sends a DECISION-REQ message to every other participant q
- if q has decided, then it sends its decision value to p, which decides accordingly
- if q has not yet voted, then it decides ABORT, and sends ABORT to p
- What if q is uncertain? Then cannot help p

Logging actions

1. When c sends VOTE-REQ, it writes START-2PC to its DT Log
2. When p_i is ready to vote YES,
   i. p_i writes YES to DT Log
   ii. p_i sends YES to c (p_i writes also list of participants)
3. When p_i is ready to vote NO, it writes ABORT to DT Log
4. When c is ready to decide COMMIT, it writes COMMIT to DT Log before sending COMMIT to participants
5. When c is ready to decide ABORT, it writes ABORT to DT Log
6. After p_i receives decision value, it writes it to DT Log

p recovers

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- if DT Log contains START-2PC, then $p = c$:
  - if DT Log contains a decision value, then decide accordingly
  - else decide ABORT

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- if DT Log contains START-2PC, then $p = c$:
  - if DT Log contains a decision value, then decide accordingly
  - else decide ABORT
- otherwise, p is a participant:
  - if DT Log contains a decision value, then decide accordingly
  - else if it does not contain a Yes vote, decide ABORT
  - else (Yes but no decision) run a termination protocol

2PC and blocking

- Blocking occurs whenever the progress of a process depends on the repairing of failures
- No AC protocol is non blocking in the presence of communication or total failures
- But 2PC can block even with non-total failures and no communication failures among operating processes!

3-Phase Commit

- Two approaches:
  1. Focus only on site failures
     - Non-blocking, unless all sites fail
     - Timeout $\equiv$ site at the other end failed
     - Communication failures can produce inconsistencies
  2. Tolerate both site and communication failures
     - partial failures can still cause blocking, but less often than in 2PC

Blocking and uncertainty

Why does uncertainty lead to blocking?

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- An uncertain process does not know whether it can safely decide COMMIT or ABORT because some of the processes it cannot reach could have decided either

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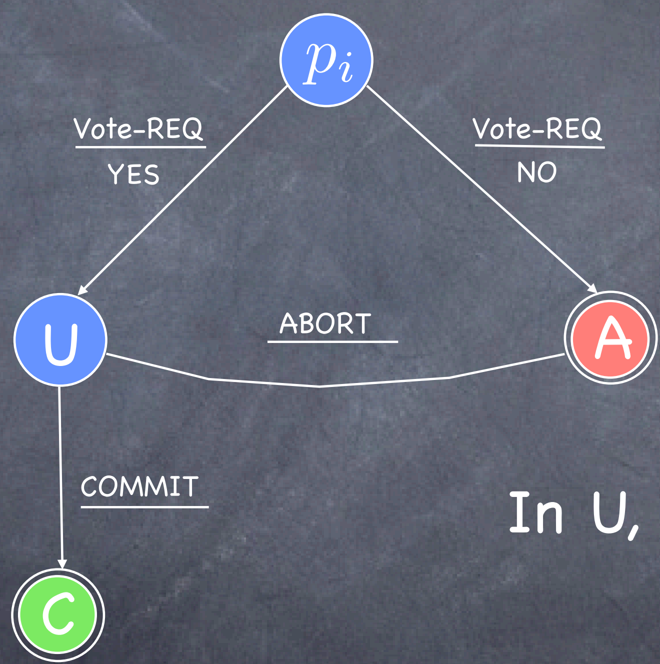
Non-blocking property (NB property)

If any operational process is uncertain, then no process has decided COMMIT

2PC Revisited



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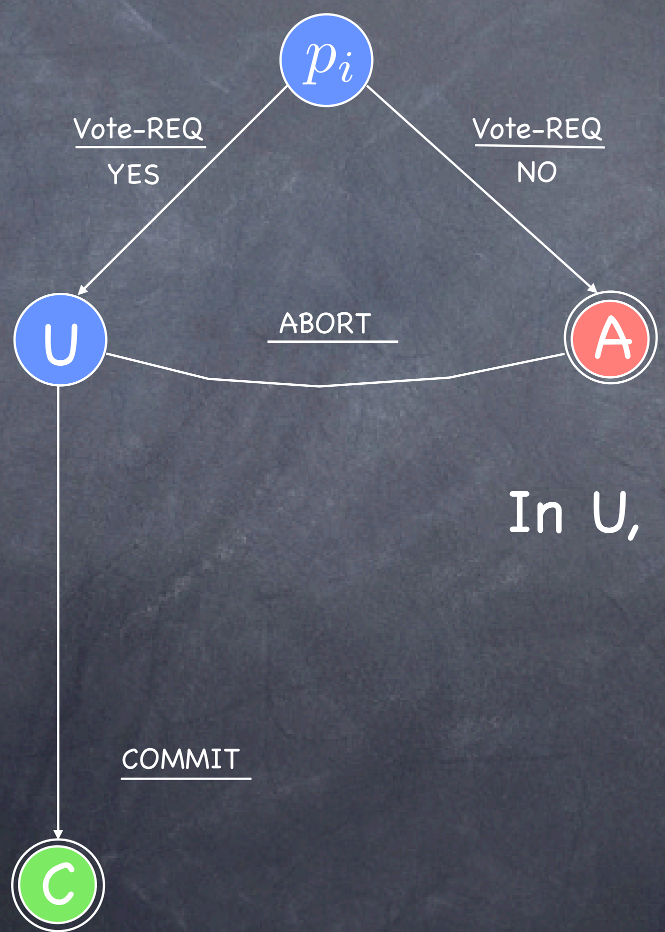

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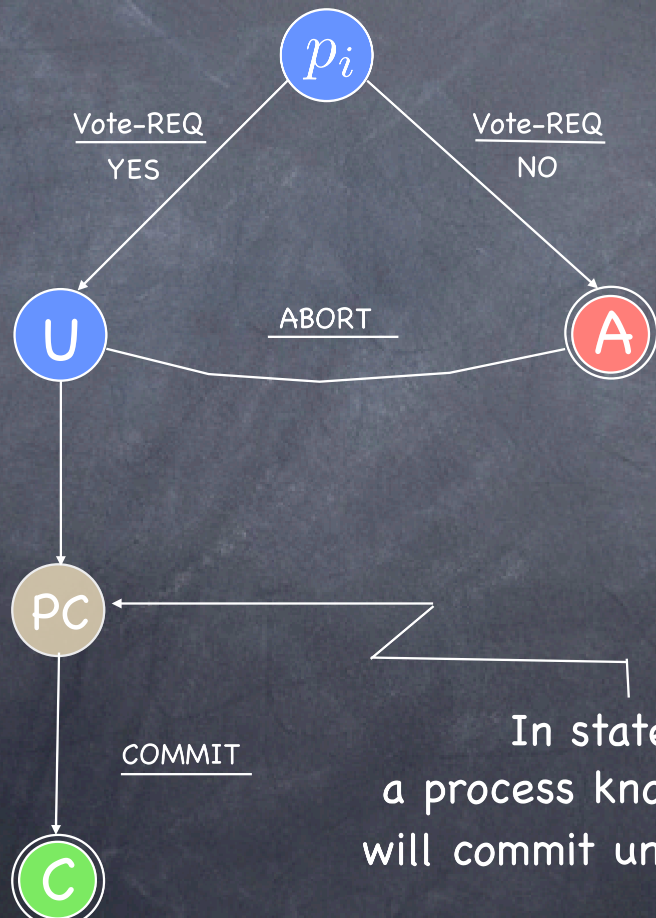

In state PC
a process knows that it
will commit unless it fails

3PC: The Protocol

Dale Skeen (1982)

I. c sends VOTE-REQ to all participants.

II. When p_i receives a VOTE-REQ, it responds by sending a vote to c
if $vote_i$ = No, then $decide_i$:= ABORT and p_i halts.

III. c collects votes from all.
if all votes are Yes, then c sends PRECOMMIT to all
else $decide_c$:= ABORT; sends ABORT to all who voted Yes
c halts

IV. if p_i receives PRECOMMIT then it sends ACK to c

V. c collects ACKs from all.
When all ACKs have been received, $decide_c$:= COMMIT;
c sends COMMIT to all.

VI. When p_i receives COMMIT, p_i sets $decide_i$:= COMMIT and halts.

Wait a minute!

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- Messages are known to the receiver before they are sent...so, why are they sent?

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6. When p_i receives COMMIT, p_i sets $decide_i$:= COMMIT
   p_i halts

- Messages are known to the receiver before they are sent...so, why **are** they sent?

They inform the recipient of the protocol's progress!

- When c receives ACK from p, it knows p is not uncertain
- When p receives COMMIT, it knows no participant is uncertain, so it can commit

Timeout Actions

Processes are waiting on steps 2, 3, 4, 5, and 6

Step 2 p_i is waiting for VOTE-REQ from coordinator	Step 3 Coordinator is waiting for vote from participants
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Step 6 p_i waits for COMMIT	Participant knows what is going to receive...

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Step 6 p_i waits for COMMIT Run some Termination protocol	Participant knows what is going to receive… but NB property can be violated!

Termination protocol: Process states

At any time while running 3 PC, each participant can be in exactly one of these 4 states:

Aborted	Not voted, voted NO, received ABORT
Uncertain	Voted YES, not received PRECOMMIT
Committable	Received PRECOMMIT, not COMMIT
Committed	Received COMMIT

Not all states are compatible

	Aborted	Uncertain	Committable	Committed
Aborted	Y	Y	N	N
Uncertain	Y	Y	Y	N
Committable	N	Y	Y	Y
Committed	N	N	Y	Y

Termination protocol

- When p_i times out, it starts an election protocol to elect a new coordinator
- The new coordinator sends STATE-REQ to all processes that participated in the election
- The new coordinator collects the states and follows a termination rule

TR1. if some process decided ABORT, then
  decide ABORT
  send ABORT to all
  halt

TR2. if some process decided COMMIT, then
  decide COMMIT
  send COMMIT to all
  halt

TR3. if all processes that reported state are uncertain, then
  decide ABORT
  send ABORT to all
  halt

TR4. if some process is committable, but none committed, then
  send PRECOMMIT to uncertain processes
  wait for ACKs
  send COMMIT to all
  halt

Termination protocol and failures

Processes can fail while executing the termination protocol...

- if c times out on p, it can just ignore p
- if c fails, a new coordinator is elected and the protocol is restarted (election protocol to follow)
- total failures will need special care...

Recovering p

- if p fails before sending YES, decide ABORT
- if p fails after having decided, follow decision
- if p fails after voting YES but before receiving decision value
  - p asks other processes for help
  - 3PC is non blocking: p will receive a response with the decision
- if p has received PRECOMMIT
  - still needs to ask other processes (cannot just COMMIT)

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  - still needs to ask other processes (cannot just COMMIT)

No need to log PRECOMMIT!

The election protocol

- Processes agree on linear ordering (e.g. by pid)
- Each p maintains set UP_p of all processes that p believes to be operational
- When p detects failure of c, it removes c from UP_p and chooses smallest q in UP_p to be new coordinator
- If $q = p$, then p is new coordinator
- Otherwise, p sends UR-ELECTED to q

A few observations

- What if p', which has not detected the failure of c, receives a STATE-REQ from q ?

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- What if p' receives a STATE-REQ from c after it has changed the coordinator to q ?

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  - it concludes that c must be faulty
  - it removes from $UP_{p'}$ every $q' < q$
- What if p' receives a STATE-REQ from c after it has changed the coordinator to q ?
  - p' ignores the request

Total failure

- Suppose p is the first process to recover, and that p is uncertain
- Can p decide ABORT?

Some processes could have decided COMMIT after p crashed!

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- p is blocked until some q recovers s.t. either
  - q can recover independently
  - q is the last process to fail–then q can simply invoke the termination protocol

Determining the last process to fail

- Suppose a set R of processes has recovered
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R contains the last process to fail if

$$\bigcap_{p \in R} UP_p \subseteq R$$