Lecture #4: Solving SMR with Crash Faults in Partial Synchrony: The Essence of Paxos & Raft

COMS 4995-001: The Science of Blockchains

URL: https://timroughgarden.org/s25/

Tim Roughgarden

Goals for Lecture #4

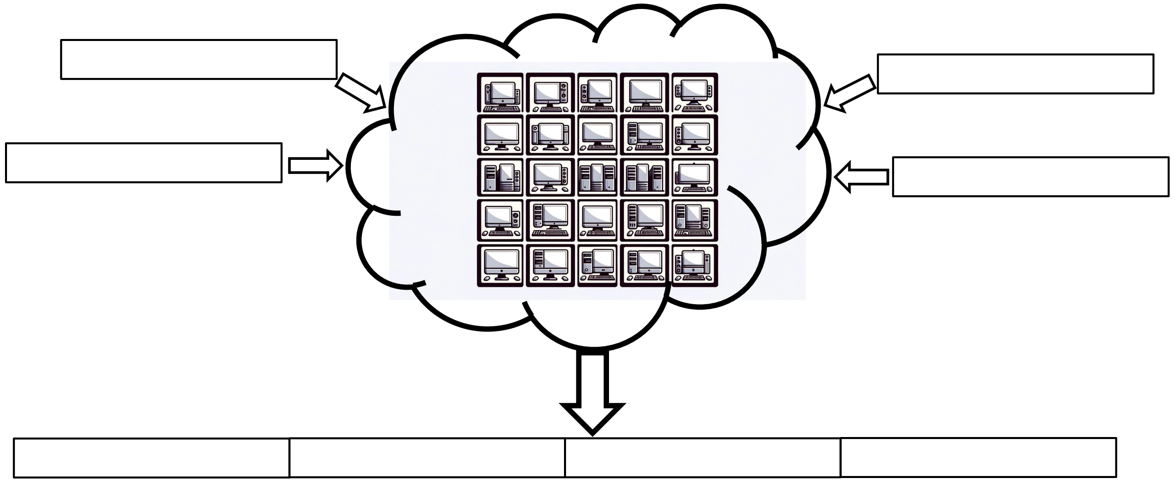
1. Understand the "partially synchronous" model.
   – useful "sweet spot" between the synchronous, asynchronous models
2. Limits on what is possible.
   – no hope unless a strict majority of validators are non-faulty
3. The Paxos/Raft protocol and its guarantees.
   – widely used in production (e.g. see the Raft Wikipedia page)

State Machine Replication (SMR)

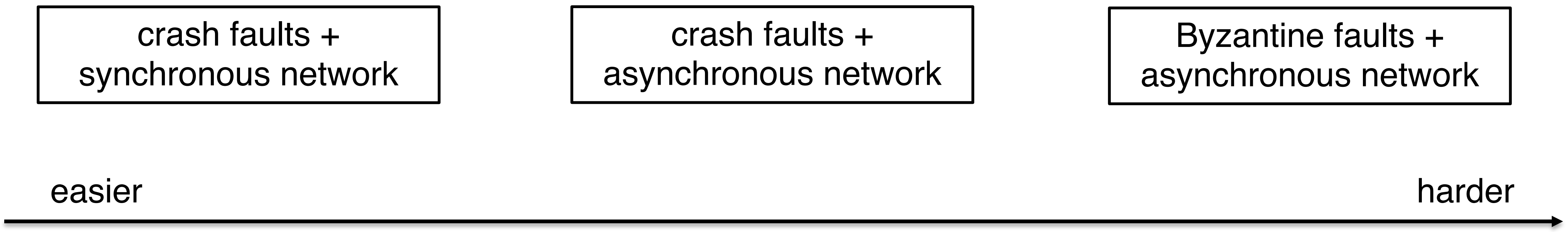
SMR: version of consensus appropriate for a blockchain protocol.

- “state machine” = for us, current state of virtual machine
- “replication” = all validators perform same state transitions
- “clients” submit transactions (“txs”) to validators
- each validator maintains an append-only list of finalized txs (a.k.a. “log” or “history”)

Goal: a protocol that satisfies consistency and liveness.



A Road Map to Practical SMR Protocols



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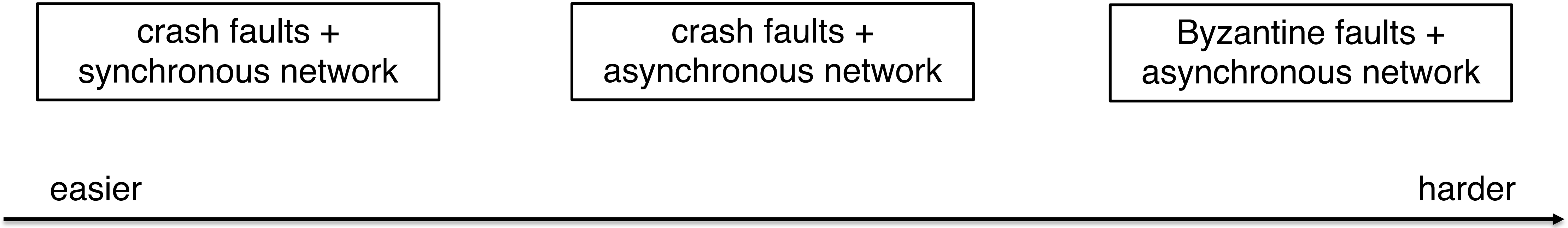

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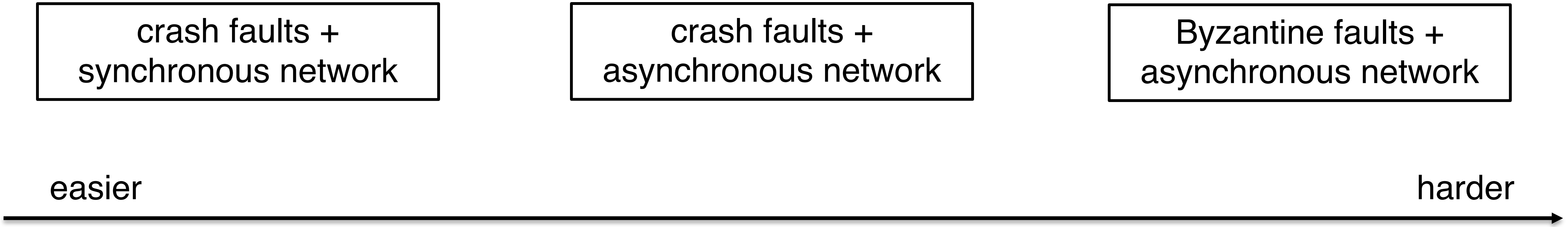

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FLP Theorem: can’t solve SMR in the asynchronous model with the threat of a single crash fault.

A Road Map to Practical SMR Protocols

crash faults + synchronous network	crash faults + ~~asynchronous~~ partially synchronous network	Byzantine faults + ~~asynchronous~~ partially synchronous network

easier → harder

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  - so protocol may stall when there's something wrong
  - FLP theorem implies must give up either consistency or liveness
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- after attack ends, quickly become live again

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- summarizing, the promises on message delivery are:
  - sent at time $t \leq GST$ ➔ arrives by time $GST + \Delta$
  - sent at time $t \geq GST$ ➔ arrives by time $t + \Delta$

Security Thresholds

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- ex: crash faults + synchrony ➔ security threshold ≈ 100%
  - Protocol B consistent and live even if only one validator remains
- ex: crash faults + asynchrony ➔ security threshold ≈ 0%
  - FLP Theorem: already hosed with a single crash fault

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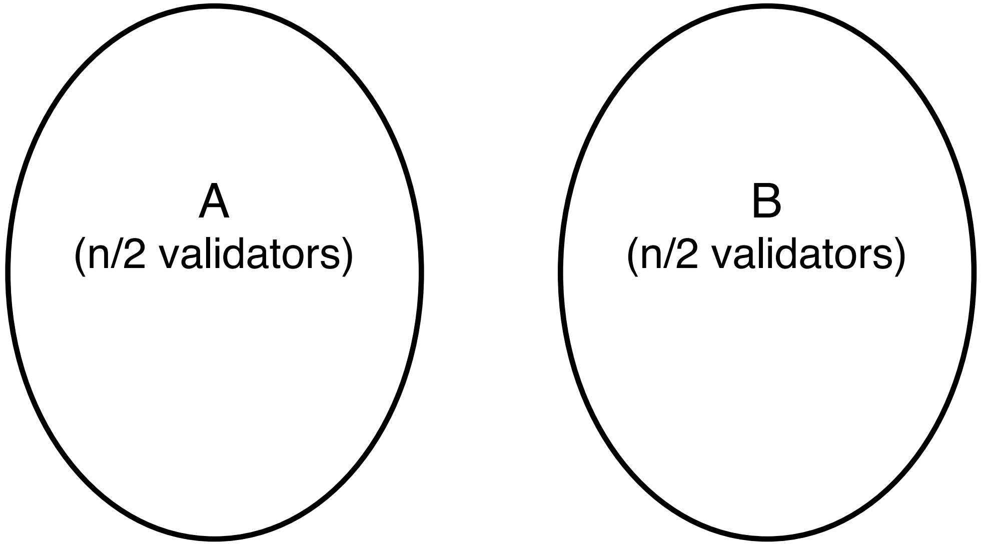

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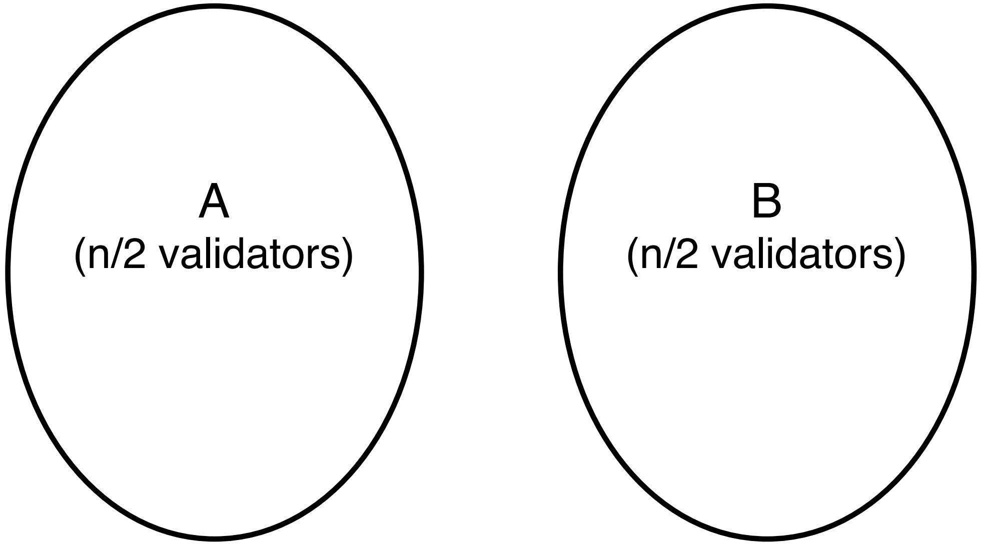

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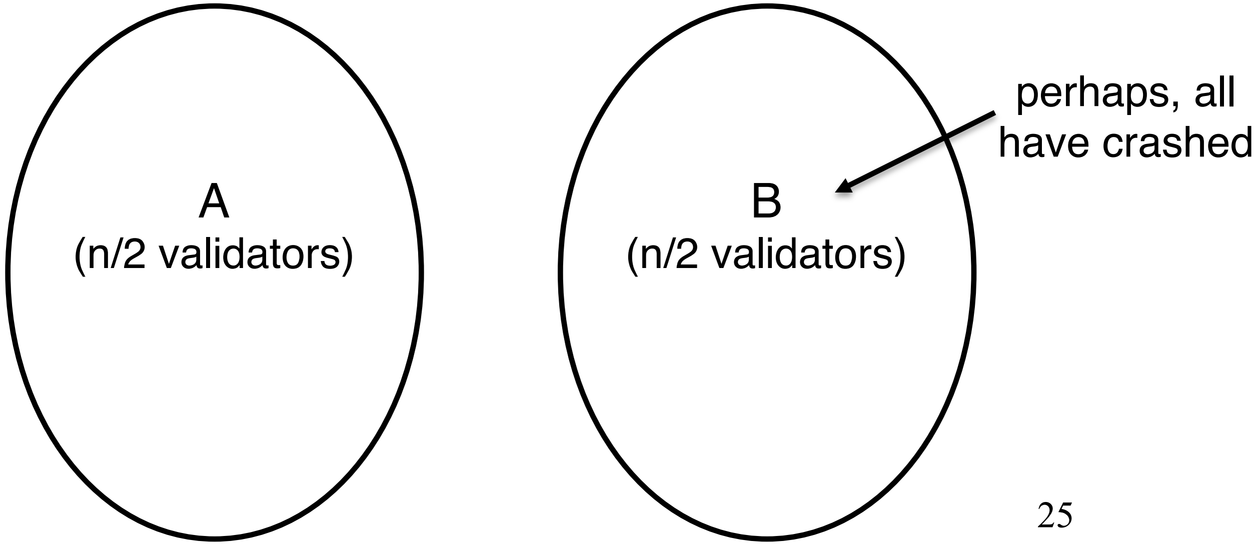

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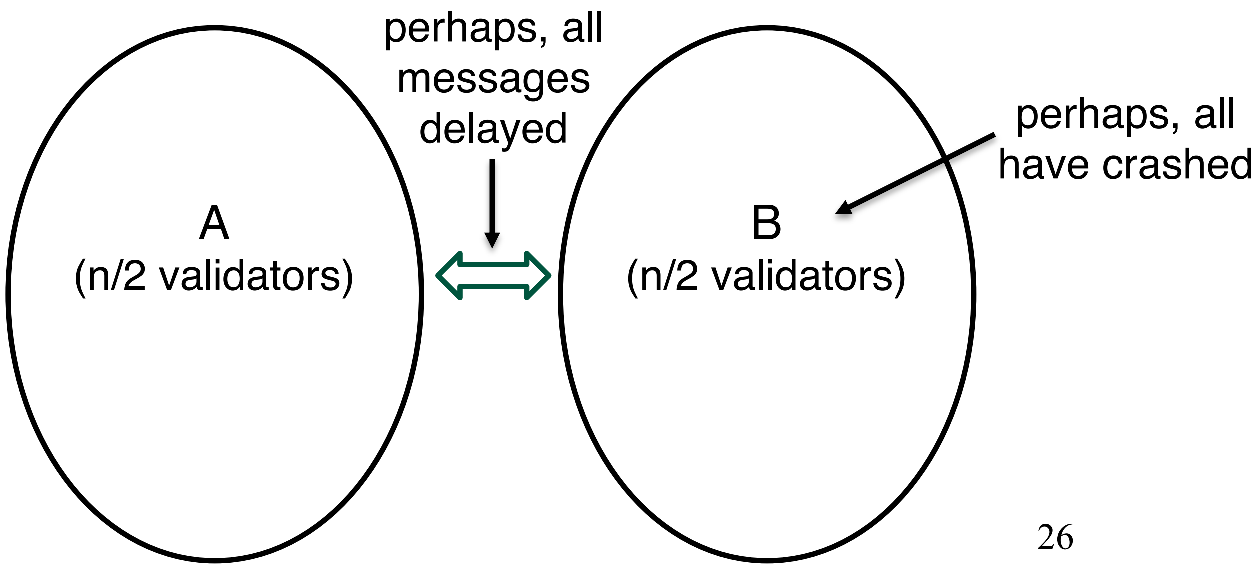

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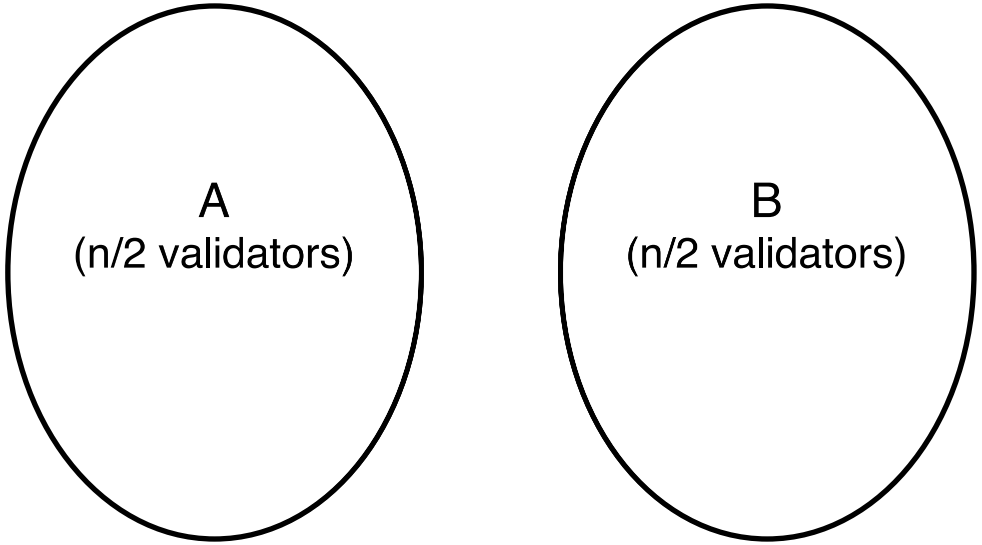

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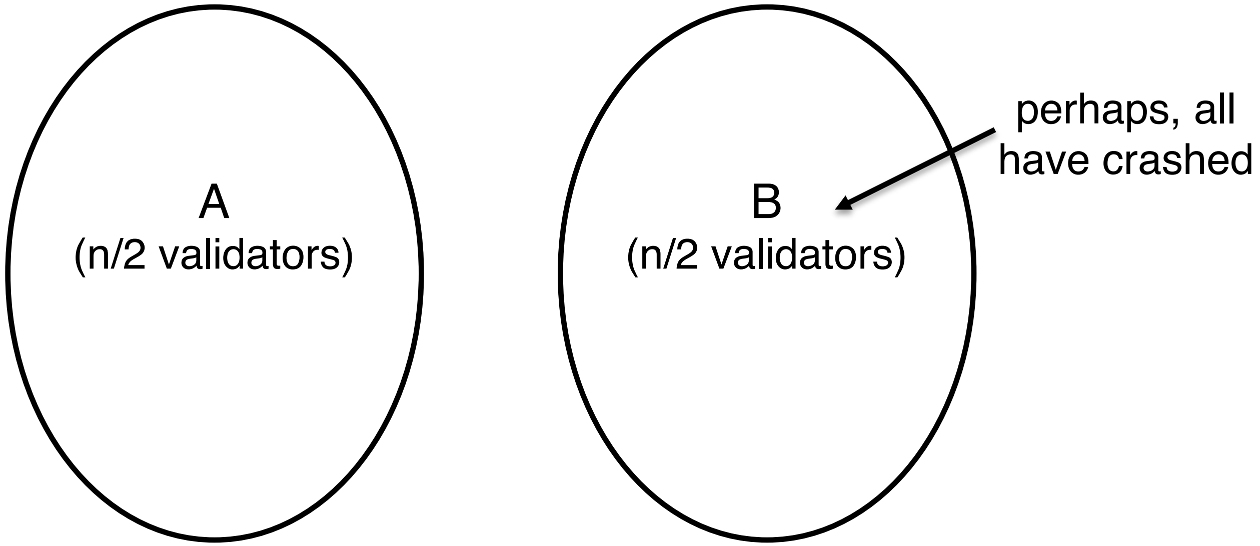

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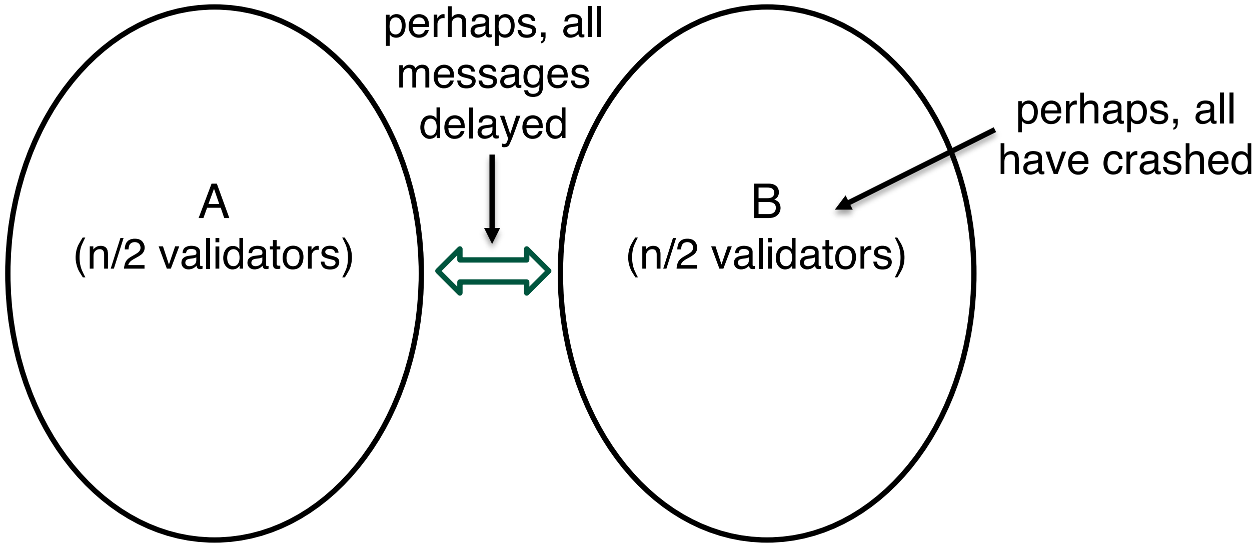

Catch-22:

- if validators in A wait ➔ possible liveness violation
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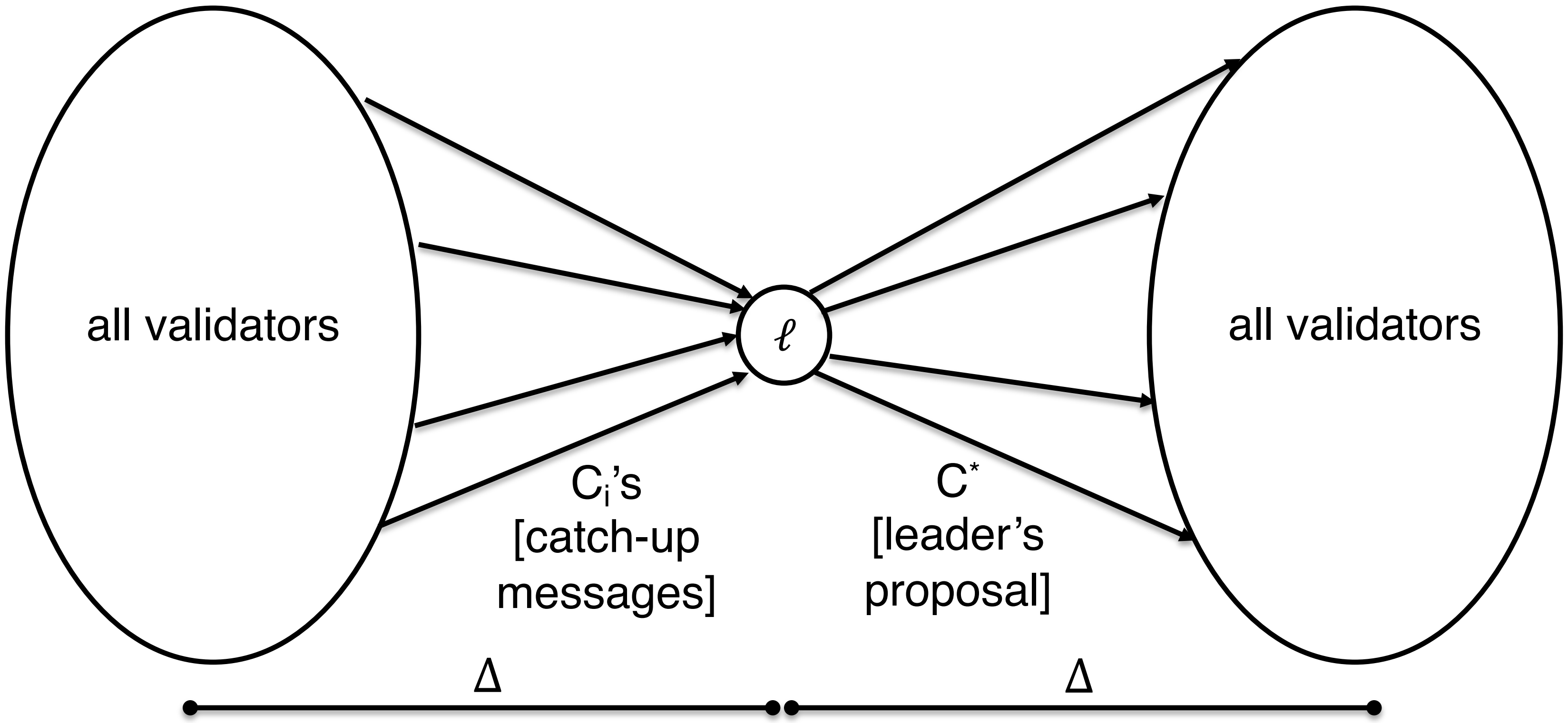
- if validators in A proceed ➔ possible consistency violation
  - if pre-GST and all messages A ⬄ B have been delayed

Design Patterns

1. views = repeated attempts to finalize new transactions.
2. leaders = coordinate the transactions proposed in each view.
   – chosen e.g. round-robin (variation: chosen randomly)
3. view may end with non-faulty validators in different states.
   – leader may need to “clean up the mess” left by previous view
4. leader should be as up-to-date as all non-faulty validators.
   – *otherwise, leader’s out-of-date proposal might conflict with the local chains of more up-to-date non-faulty validators*
   – reason for the “catch-up” messages in first half of view in Protocol B
5. distributed computing is hard! [no proof ➔ probably buggy!]

Protocol B: Picture of One View



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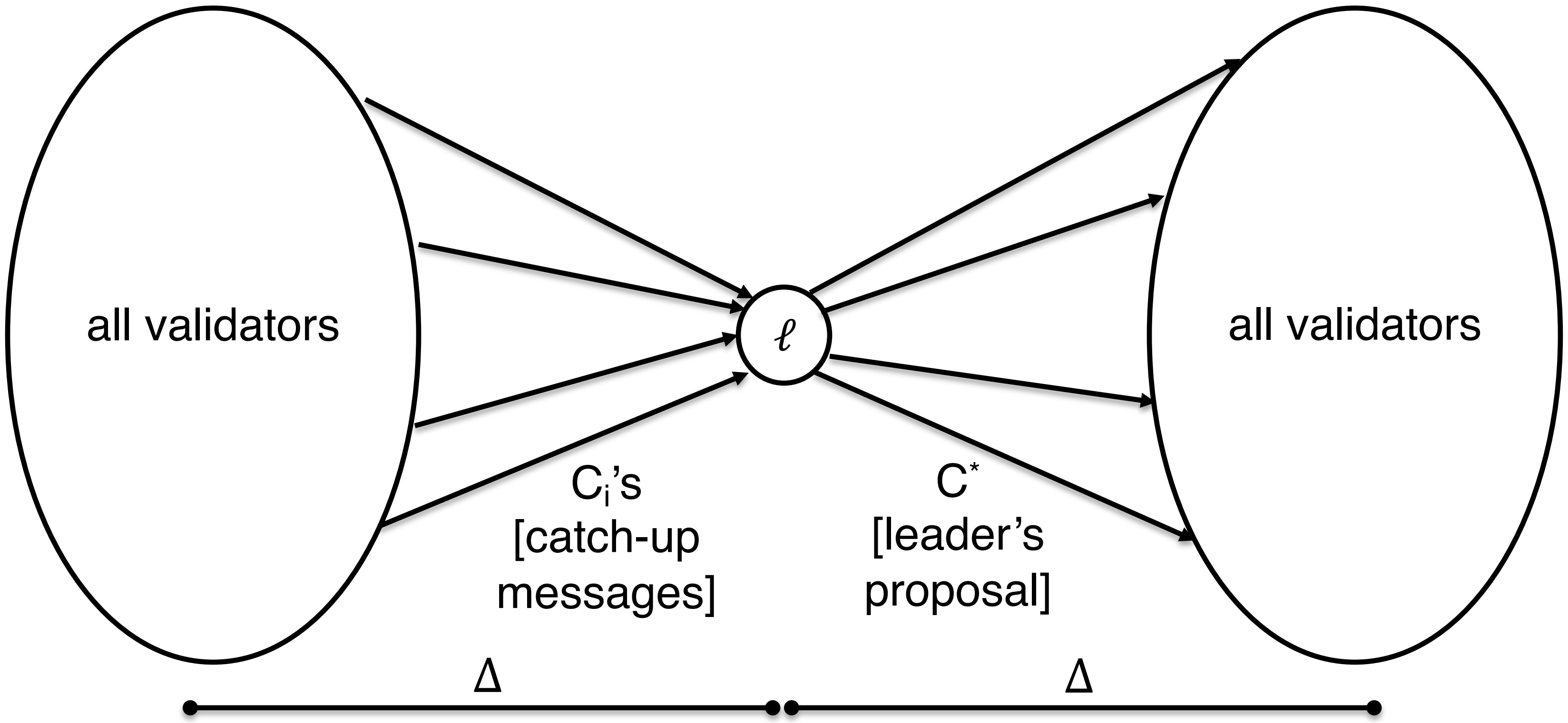

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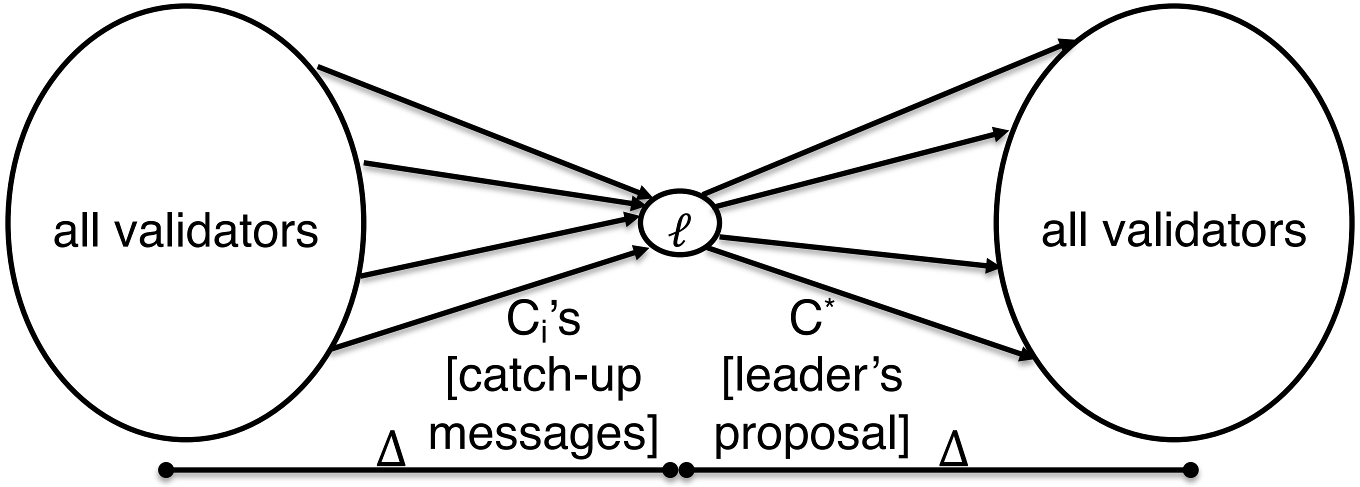

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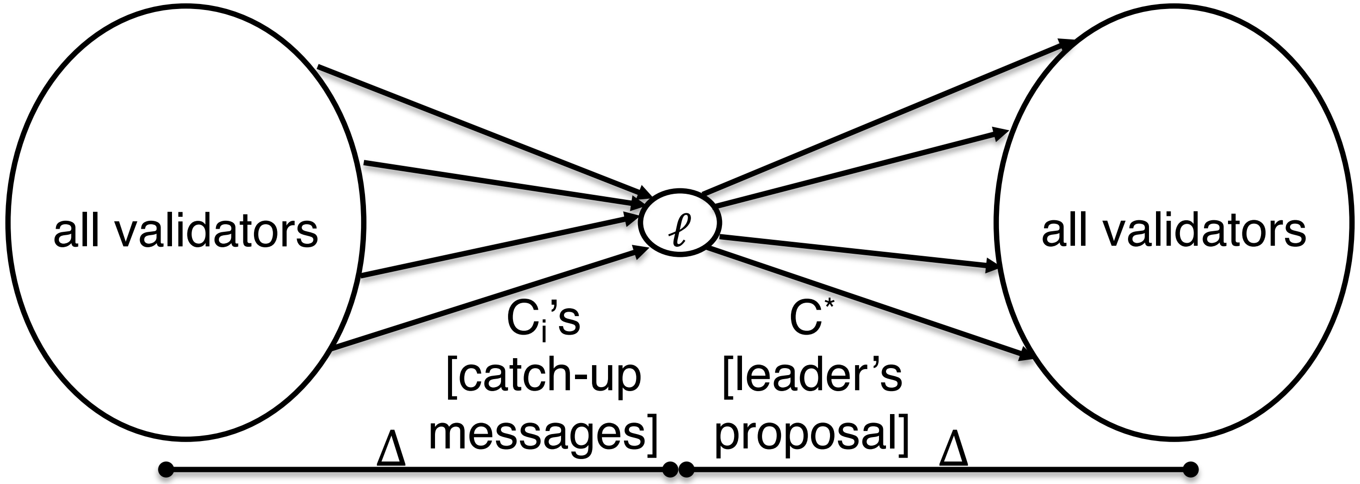

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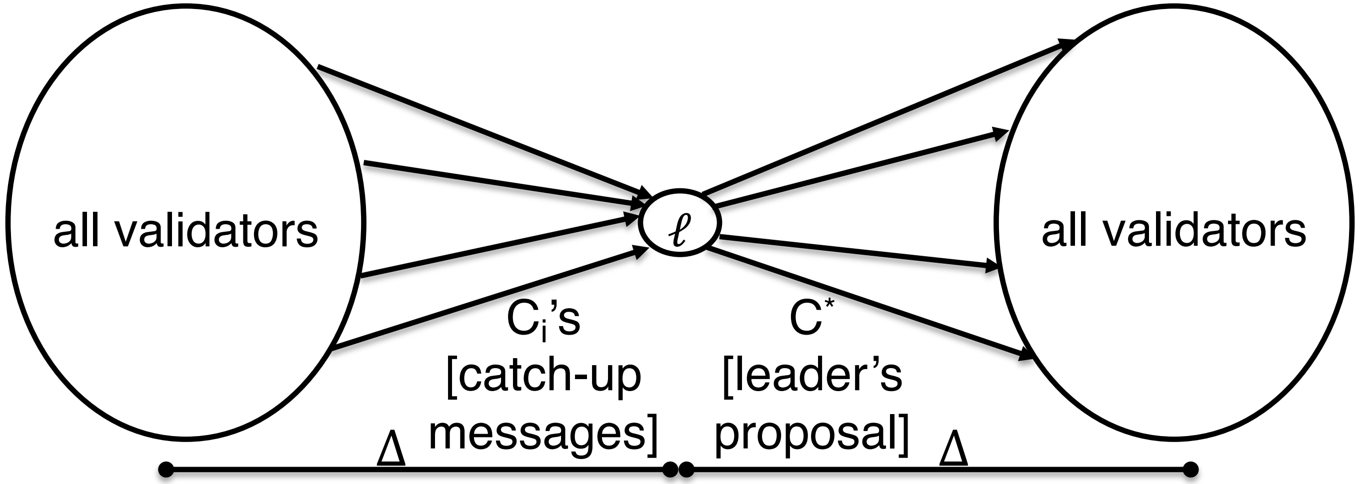

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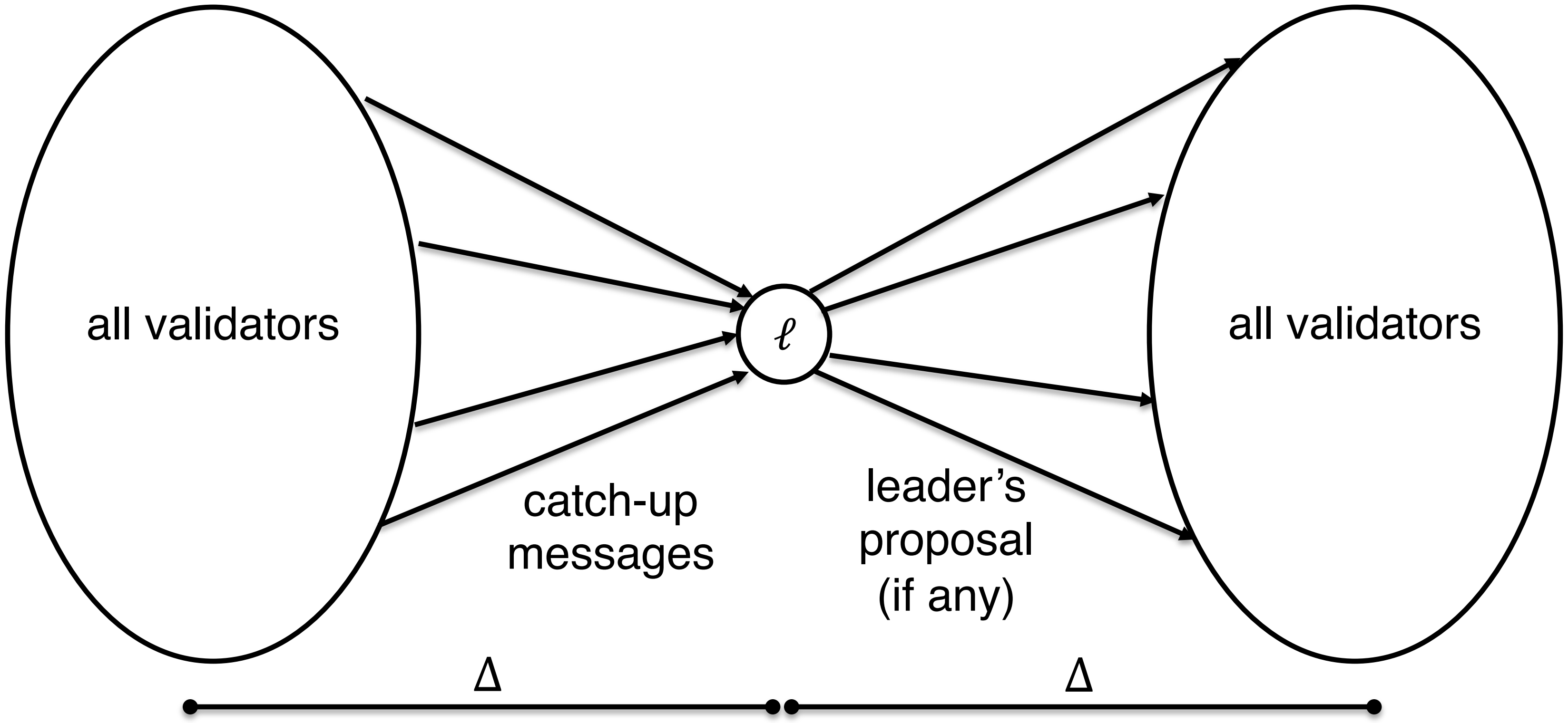

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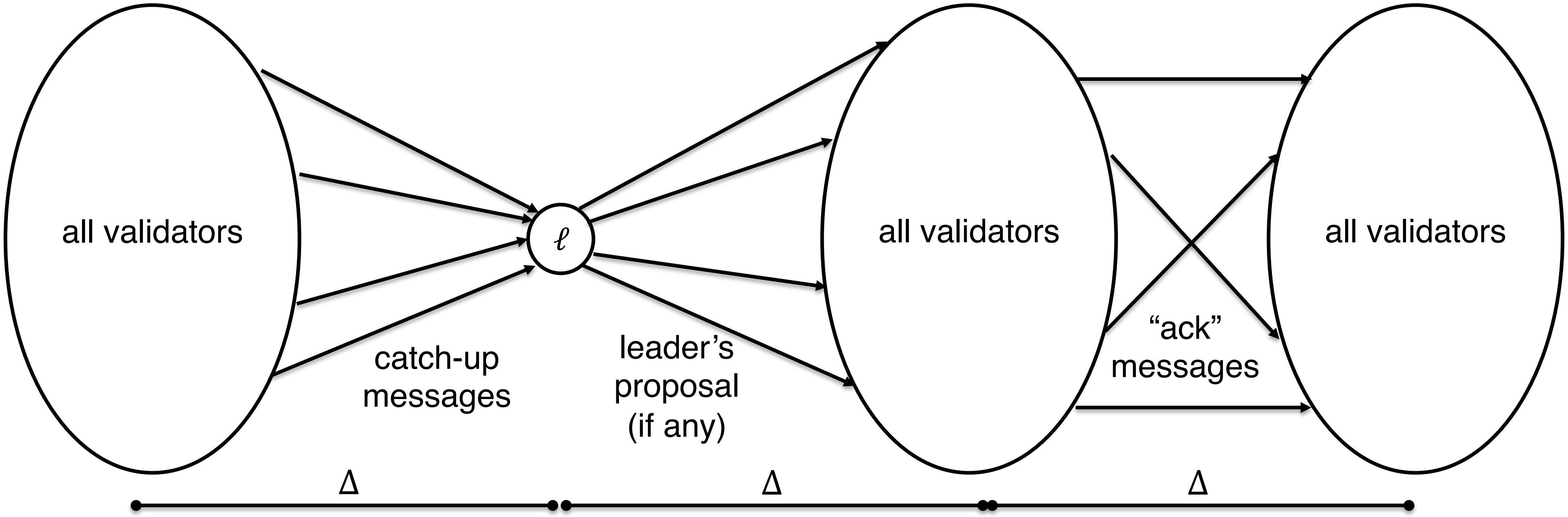

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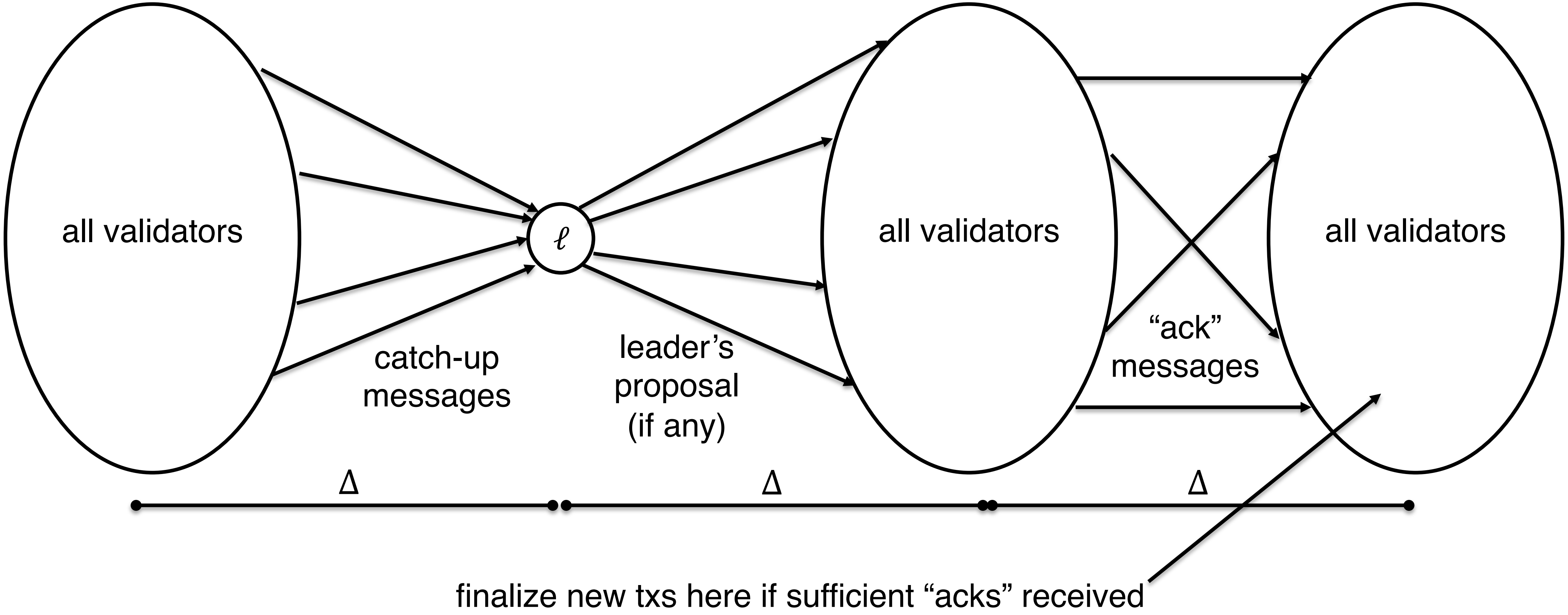

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- validator i maintains
  - a local chain C_i (i.e., sequence of blocks) of finalized txs [append-only]
  - a possibly longer chain A_i that it knows about

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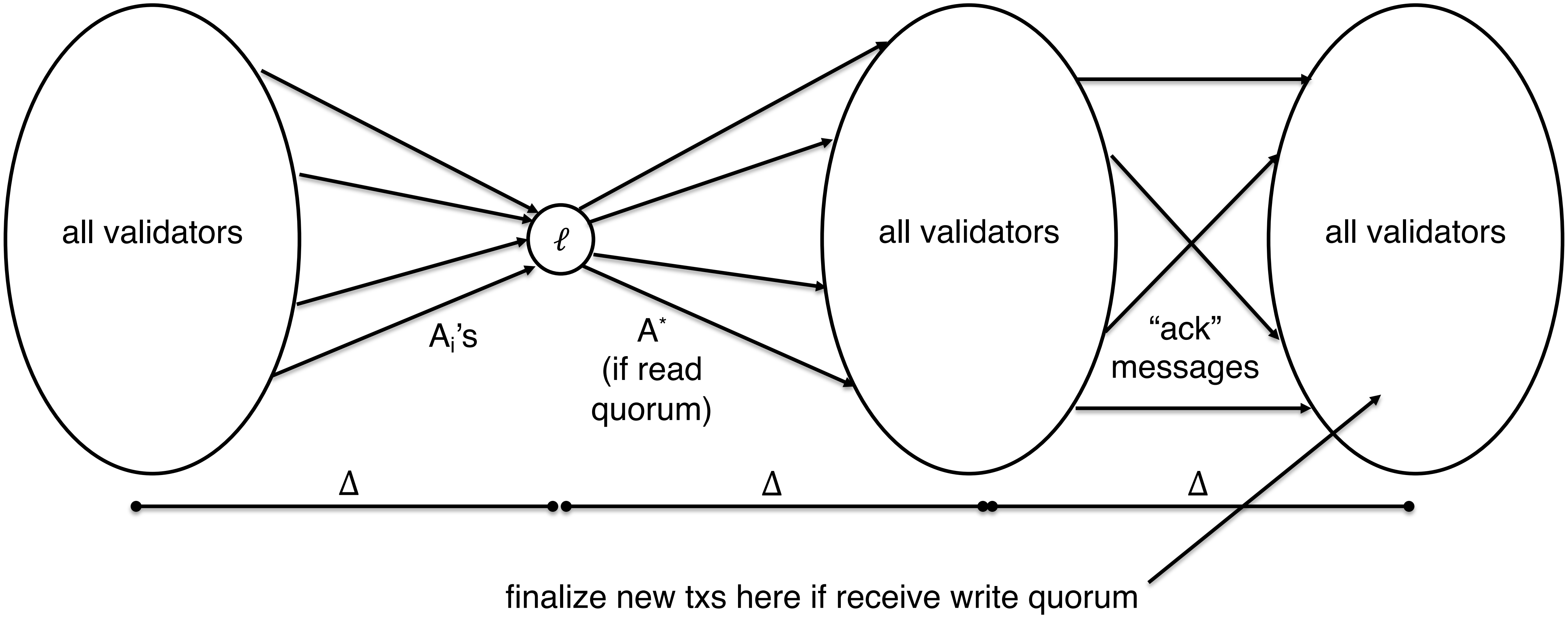

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- (2) ➔ every update extends all updates from all previous views

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Consider view v+2:

- if leader makes proposal A' ➔ let T = validators in read quorum
- *quorum intersection:* because |S|,|T|>n/2, S and T overlap
- leader receives an A_j from a view ≥v from at least one validator
- leader's proposal will extend A^* (everything from view ≥v does)

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In general (by induction on v' > v):

- if leader makes proposal A' ➔ let T = validators in read quorum
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- leader receives an A_j from a view ≥v from at least one validator
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  - ➔ all such validators set C_j := A^* at this time