Lecture #3: Solving SMR with Crash Faults and Synchrony

COMS 4995-001:
The Science of Blockchains

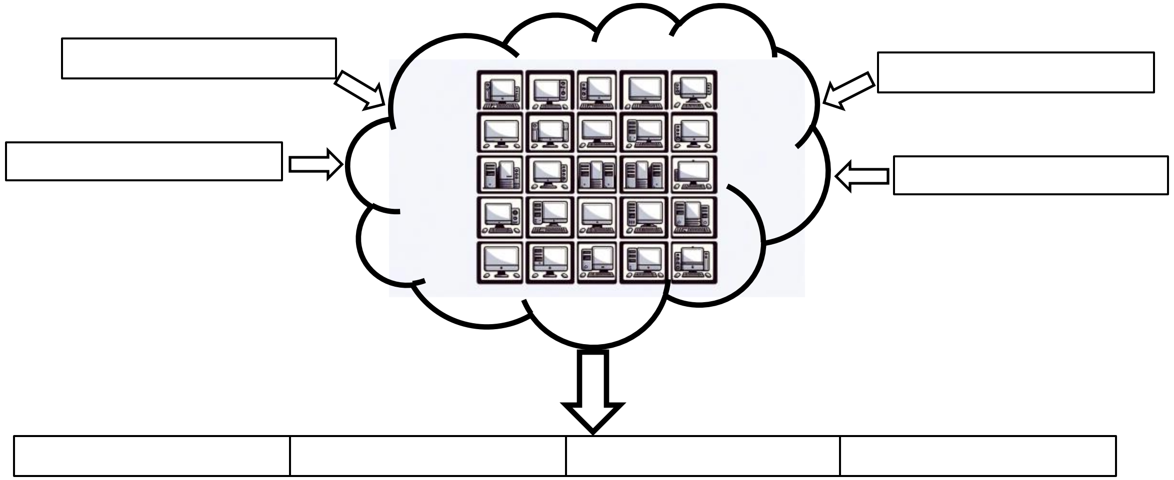
URL: https://timroughgarden.org/s25/

Tim Roughgarden

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”)



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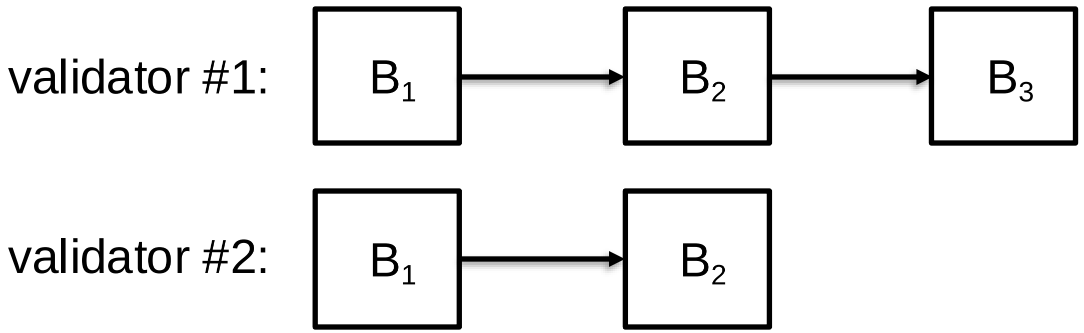

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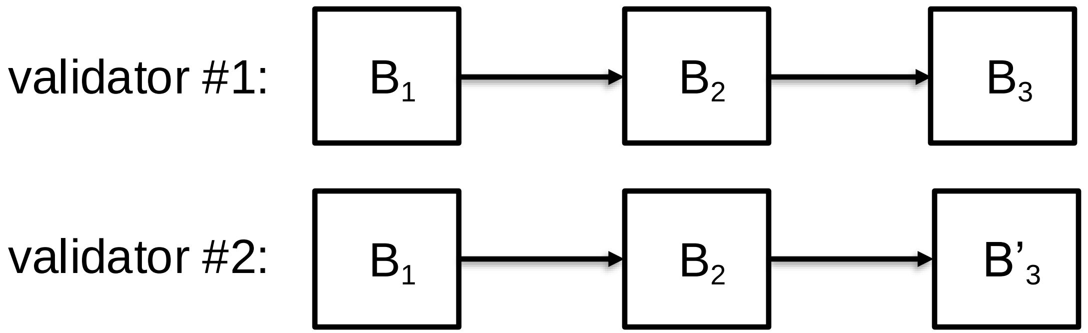

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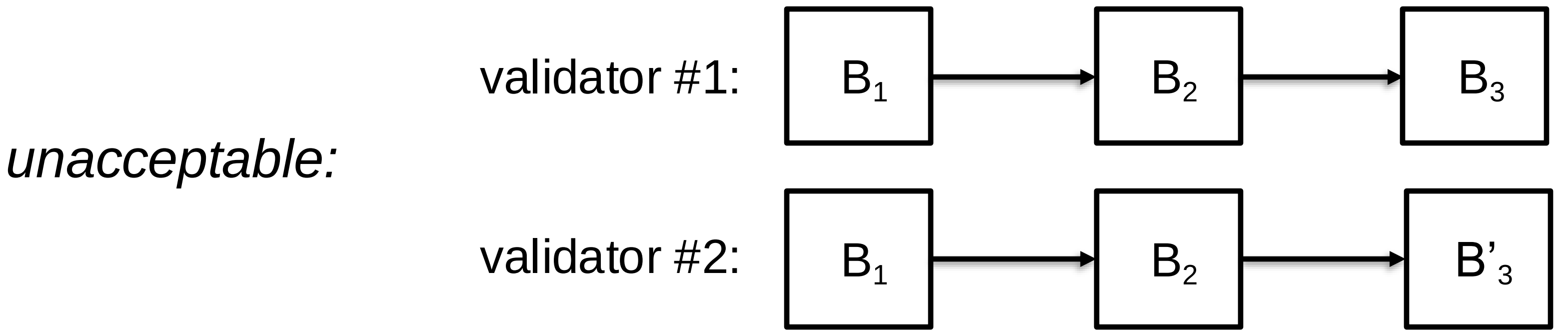

Liveness: every valid transaction submitted by a client eventually added to validators' local histories/chains.

A Road Map to Practical SMR Protocols

easier harder

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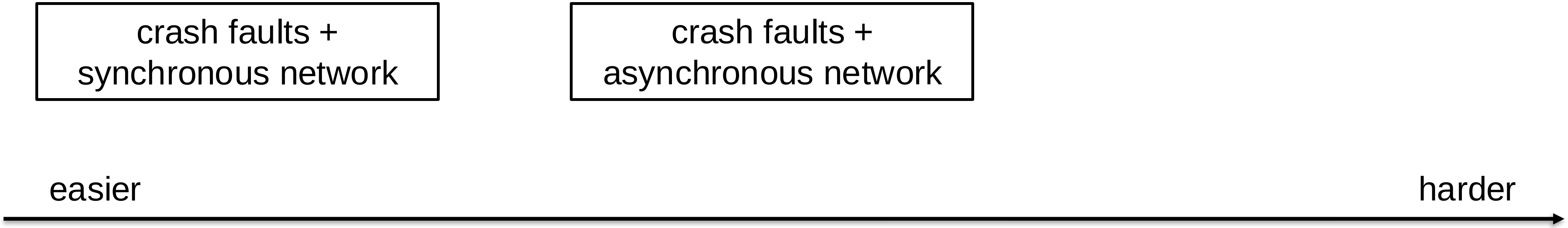

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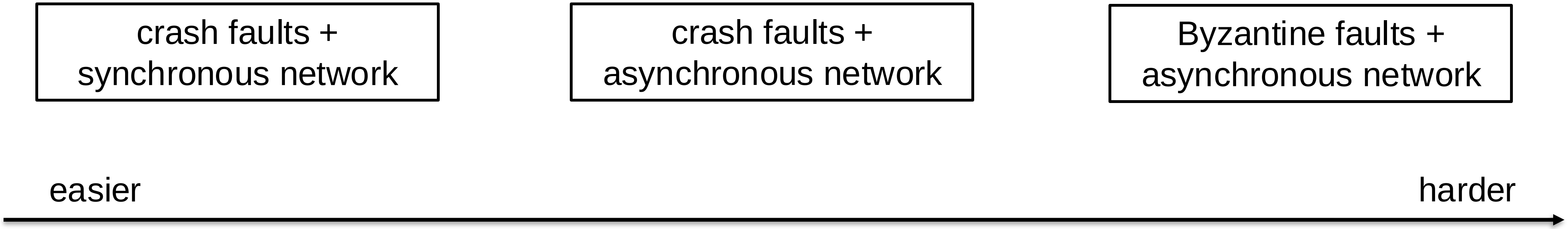

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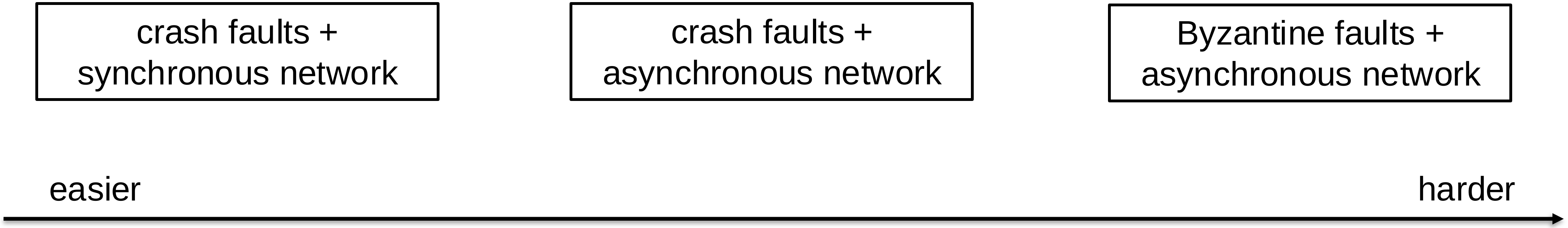

Expectations:

1. More positive results (i.e., good SMR protocols) toward the left.
2. More impossibility results (i.e., SMR unsolvable) toward the right.
3. Simpler protocols toward the left, more complex toward the right.

Goals for Lecture #3

1. The challenge of crash faults.
   – simple, but already messes up Protocol A from last time

2. Solving SMR with crash faults and a synchronous network.
   – already forces us to introduce some important design principles
   – good warm-up for more challenging and blockchain-relevant settings

3. Asynchrony: challenges and compromises.
   – an impossibility result motivates a “sweet spot” synchronous-asynchronous hybrid model

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Recall: Protocol A [code run by every validator]

- define "view" = Δ consecutive timesteps
- validators take turns as leader (round-robin, one per view)
  - plays the role of a temporary dictator (to coordinate others)
  - recall assumptions of known validator set, shared global clock

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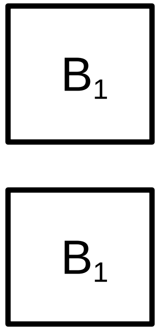
- at time $\Delta \cdot v + \Delta$: [i.e., at end of view v, before view v+1]
  - if validator i received a block B from the leader by this time:
    - validator i appends B to its local history

Why Protocol A Can't Handle Crashes

Problem: leader might crash after sending B to some but not all validators [➔ could lead to a consistency violation].



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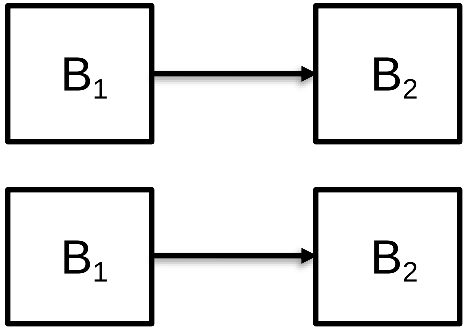

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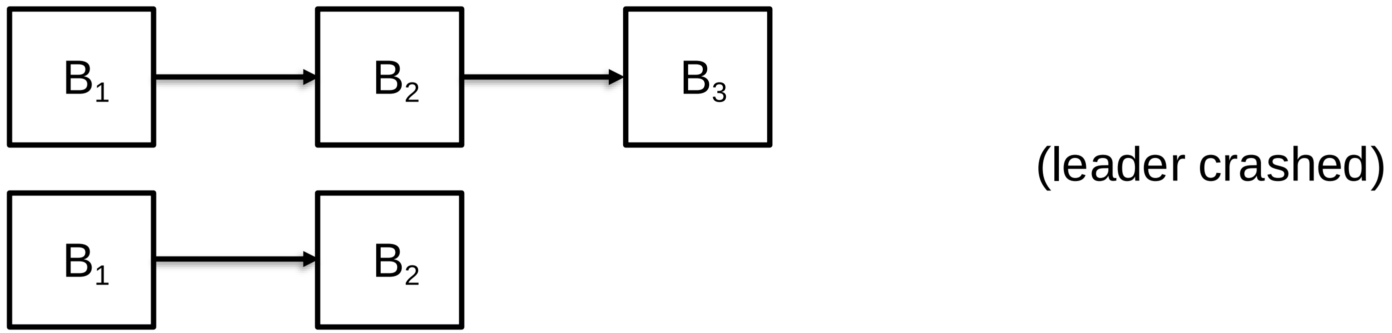

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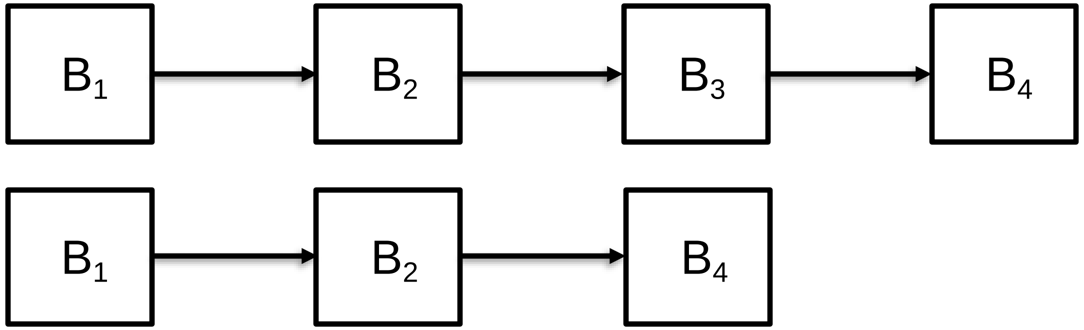

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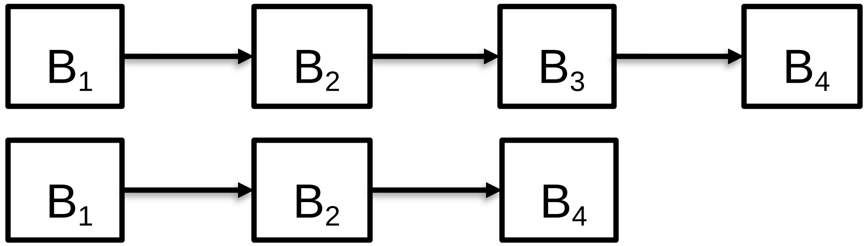

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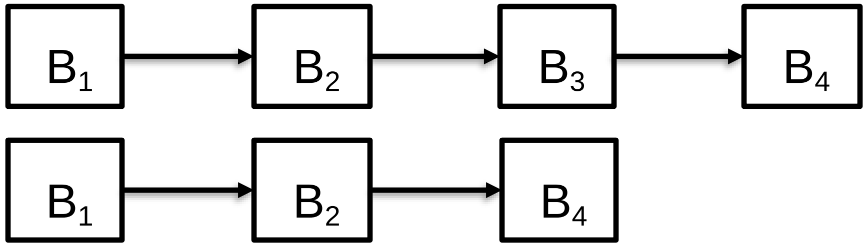

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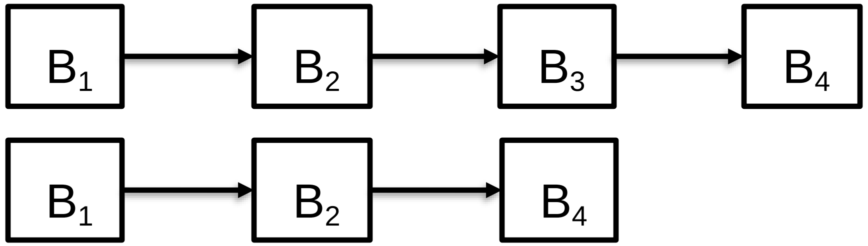

Fix:

1. validators update next leader as to their current history
   – to make sure leader is up-to-date before proposing
2. send entire history/chain, not just latest block
   – crashes ➔ validator may learn about many new blocks at same time
   – will make more practical using commitments in Part II

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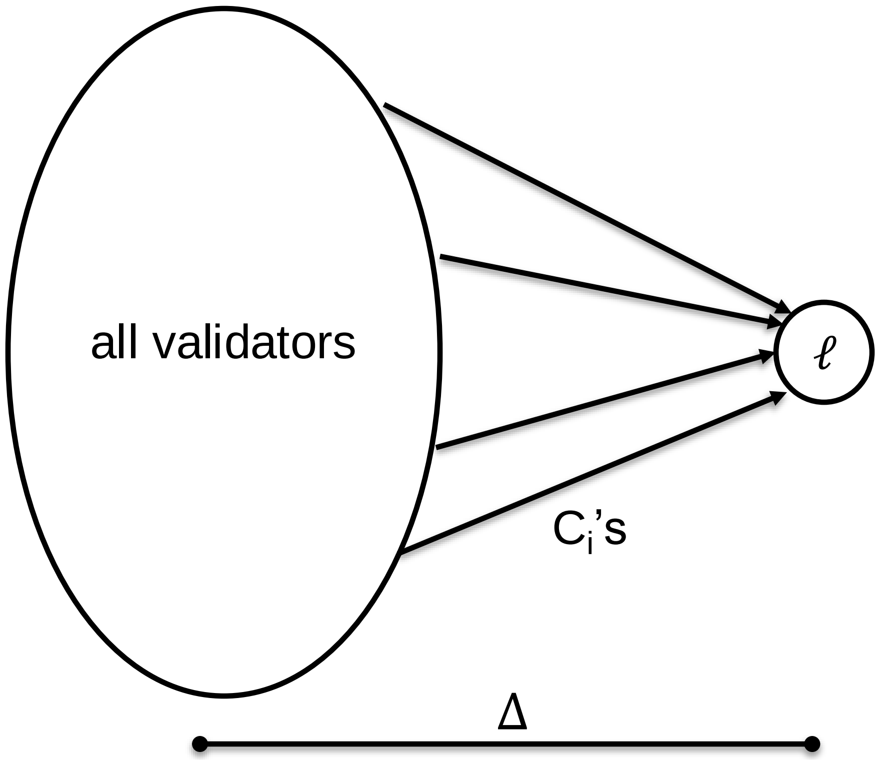
  - if validator i receives a new chain C^* from ℓ by this time:
    - validator i updates $C_i := C^*$

Picture of One View



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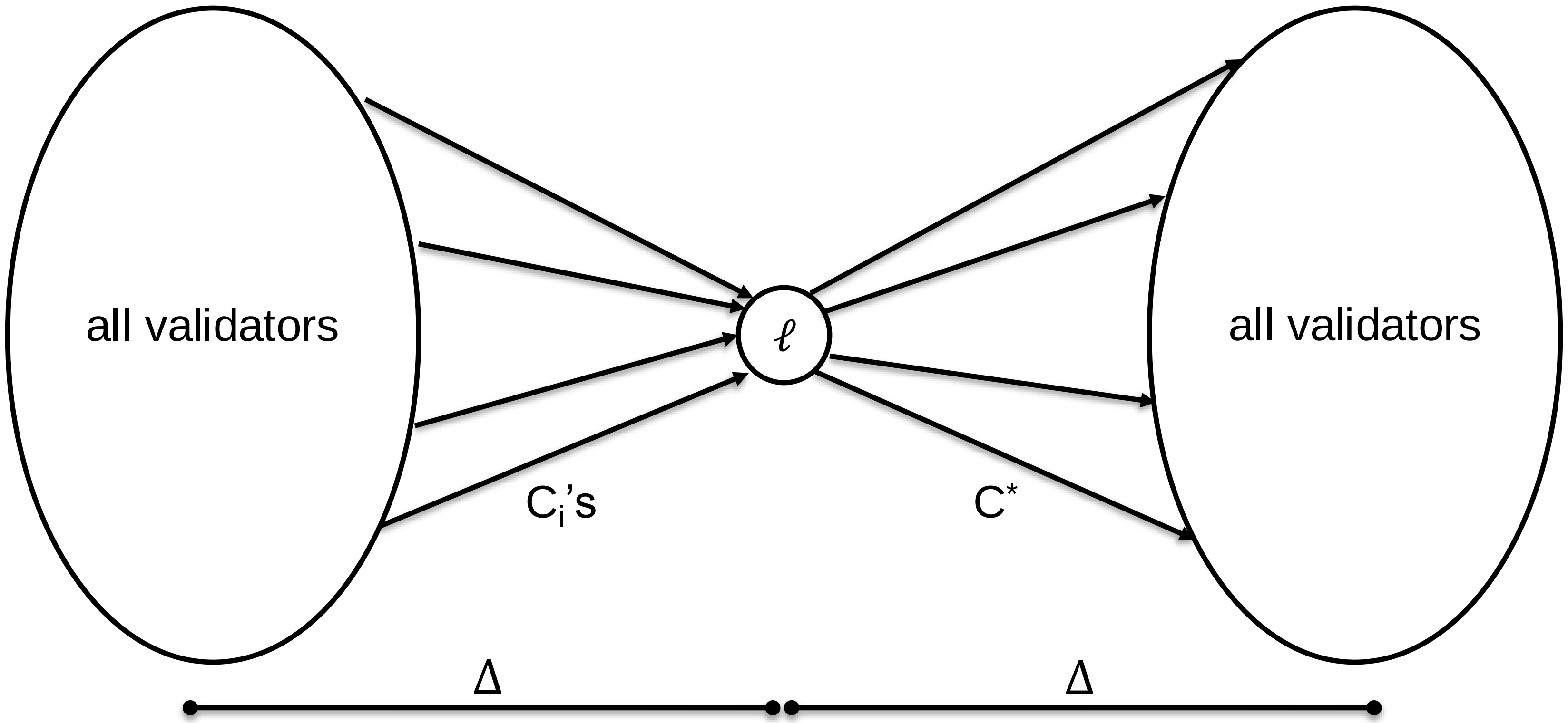

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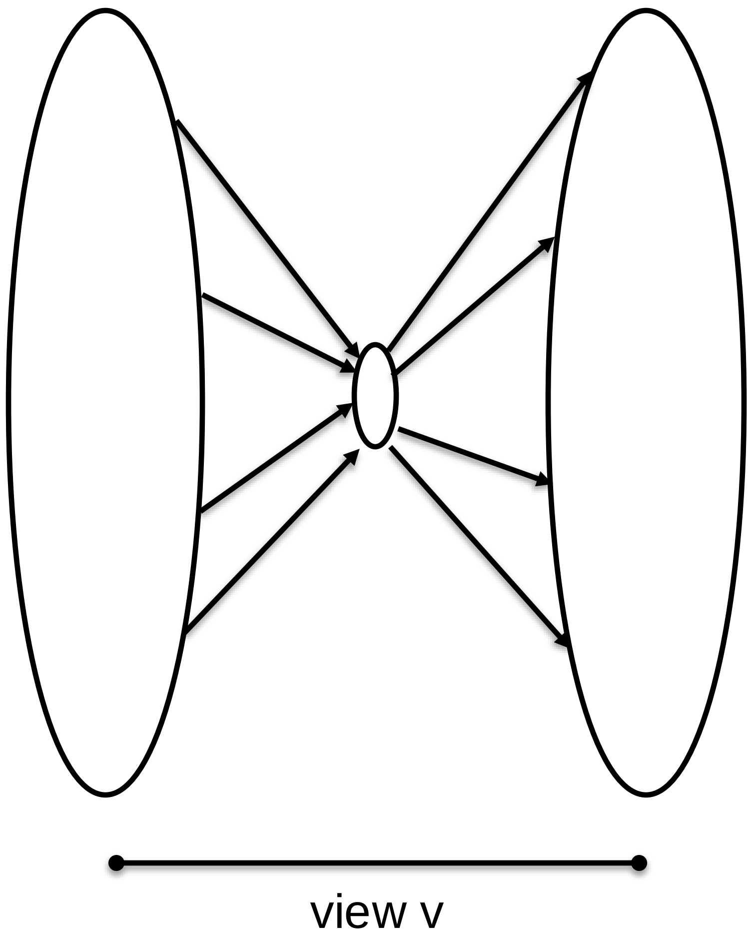

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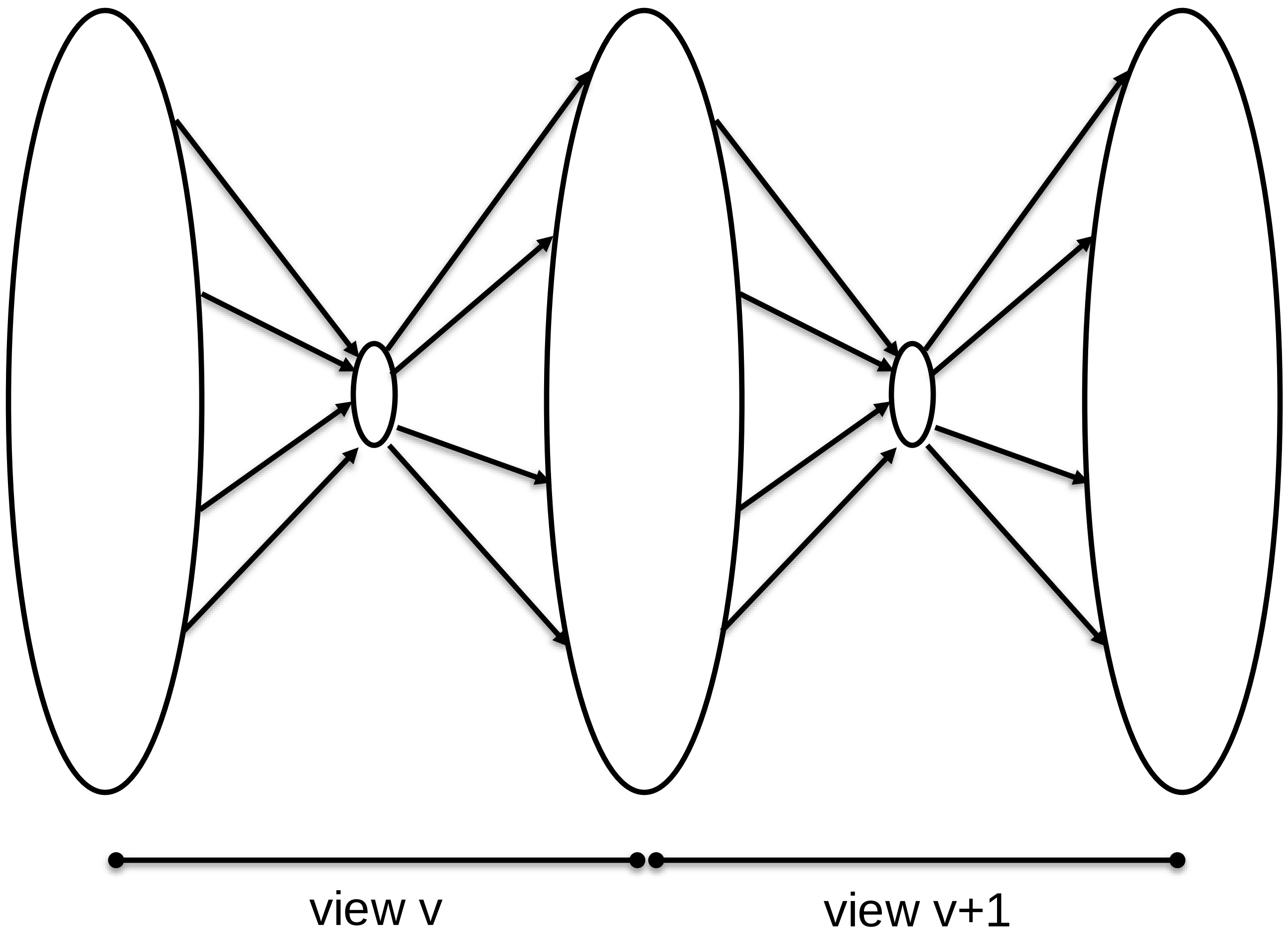

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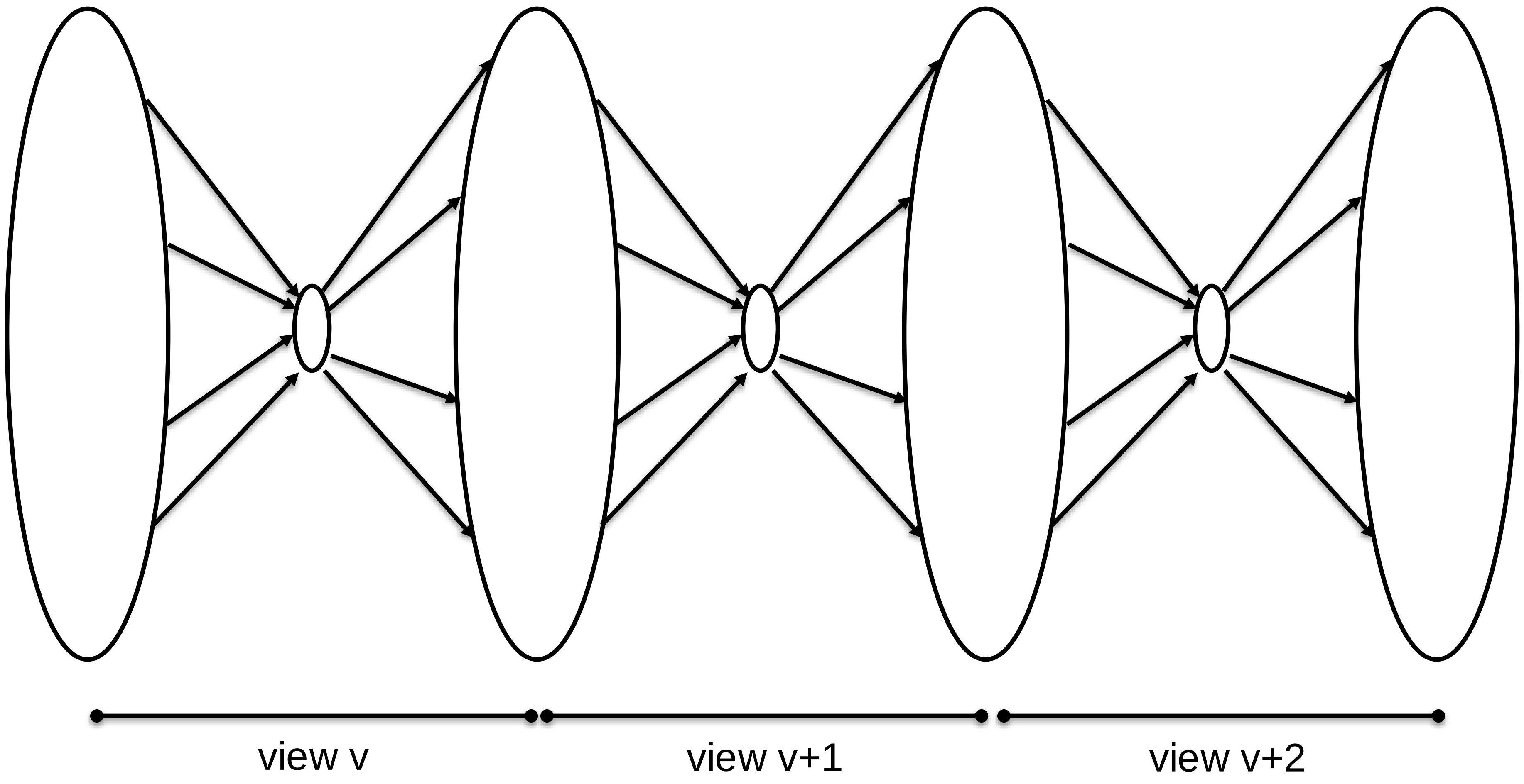

Protocol B: An Example Execution

validator 1:

validator 2:

validator 3:

validator 4:

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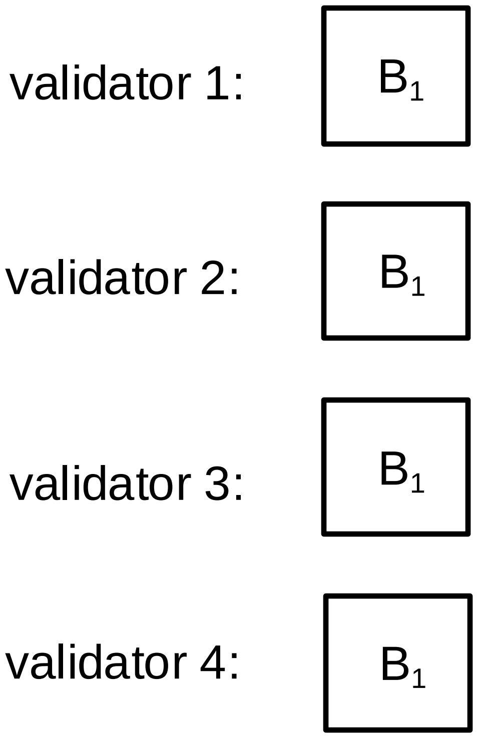

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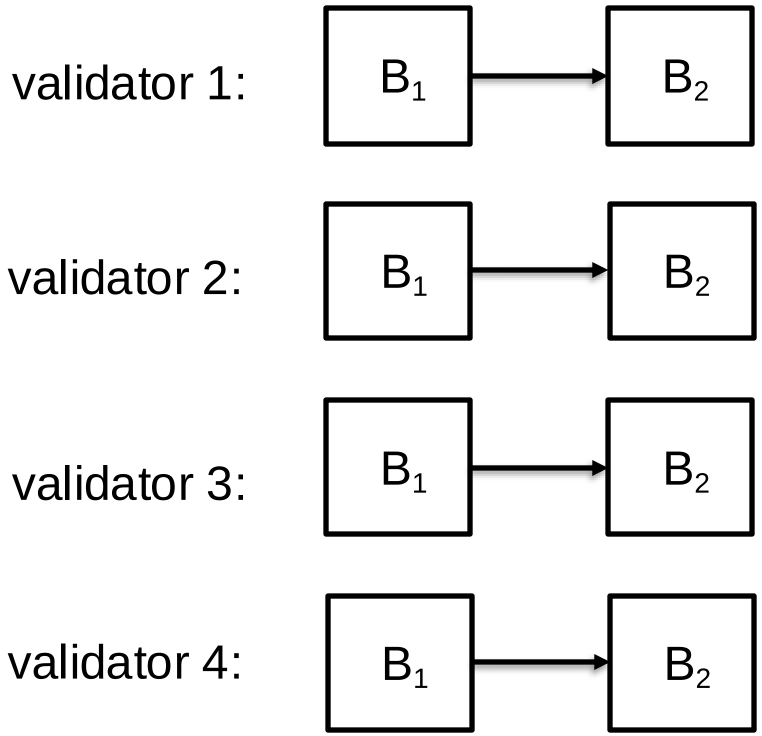

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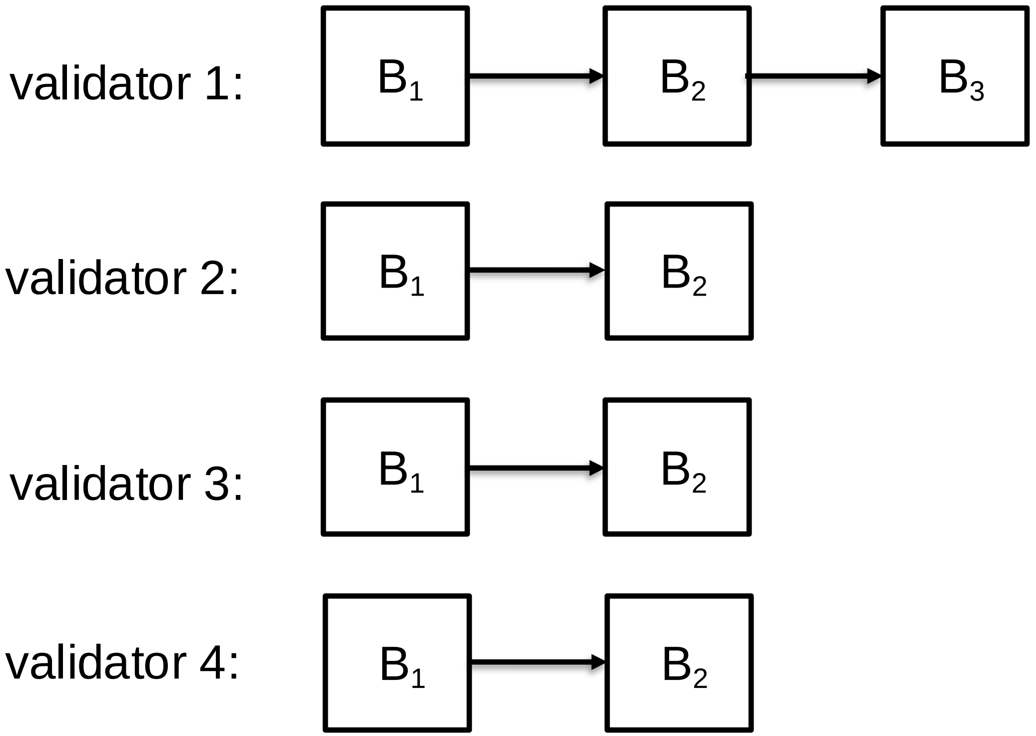

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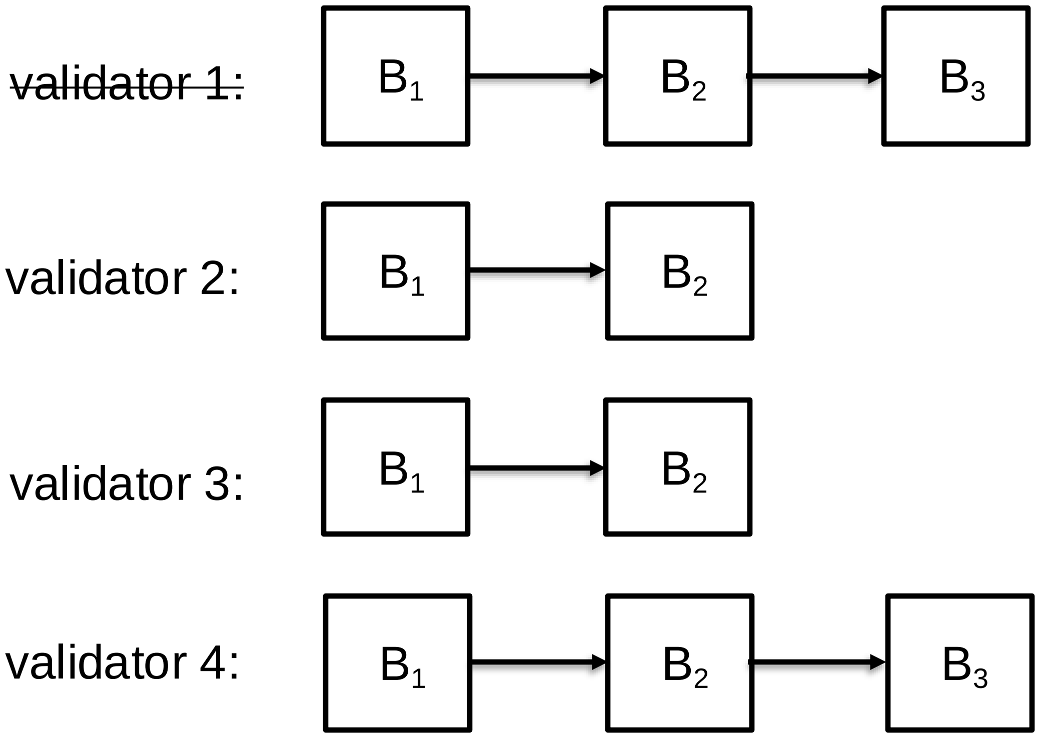

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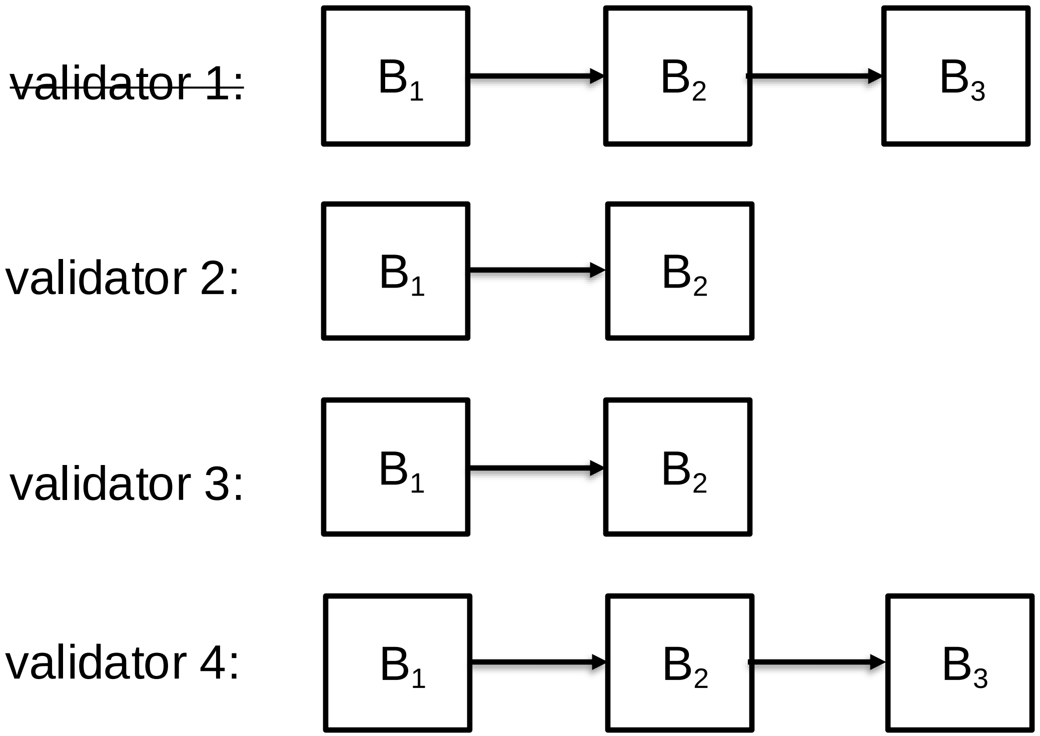

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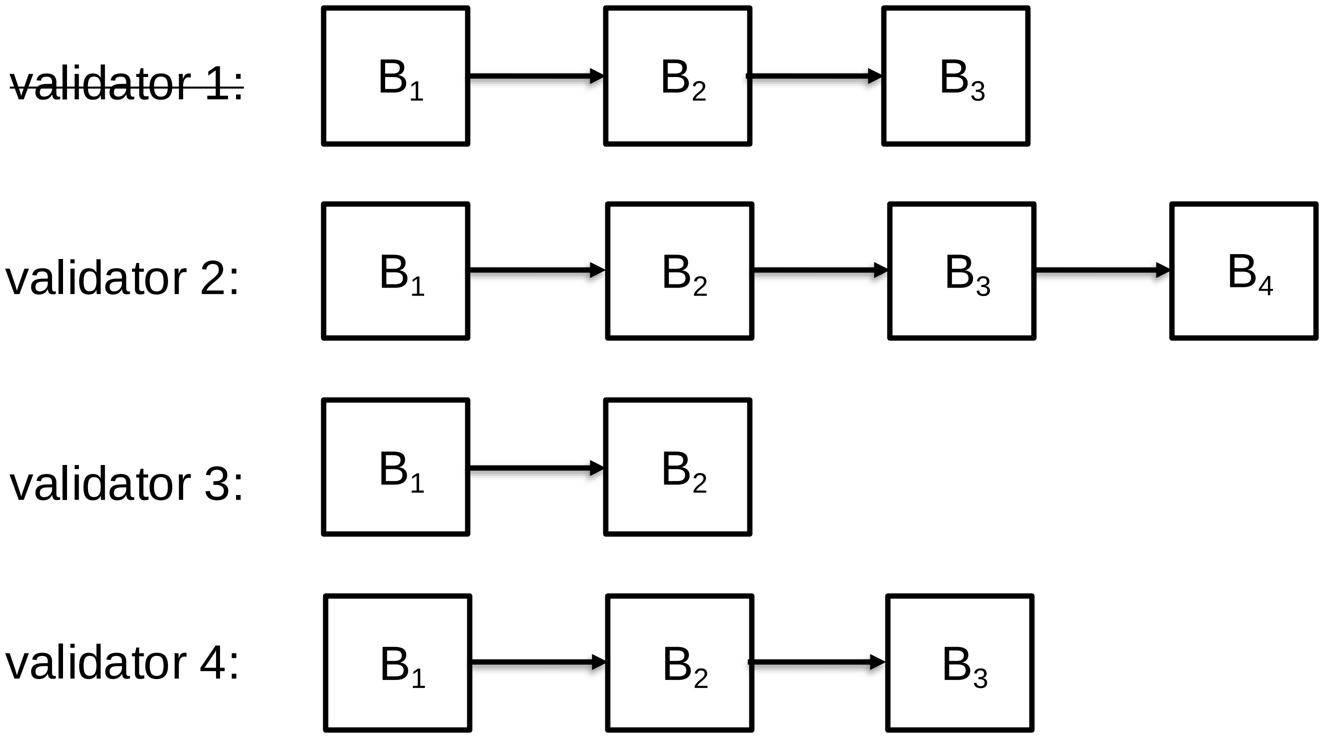

(validator 2 is next leader, prepares its proposal)

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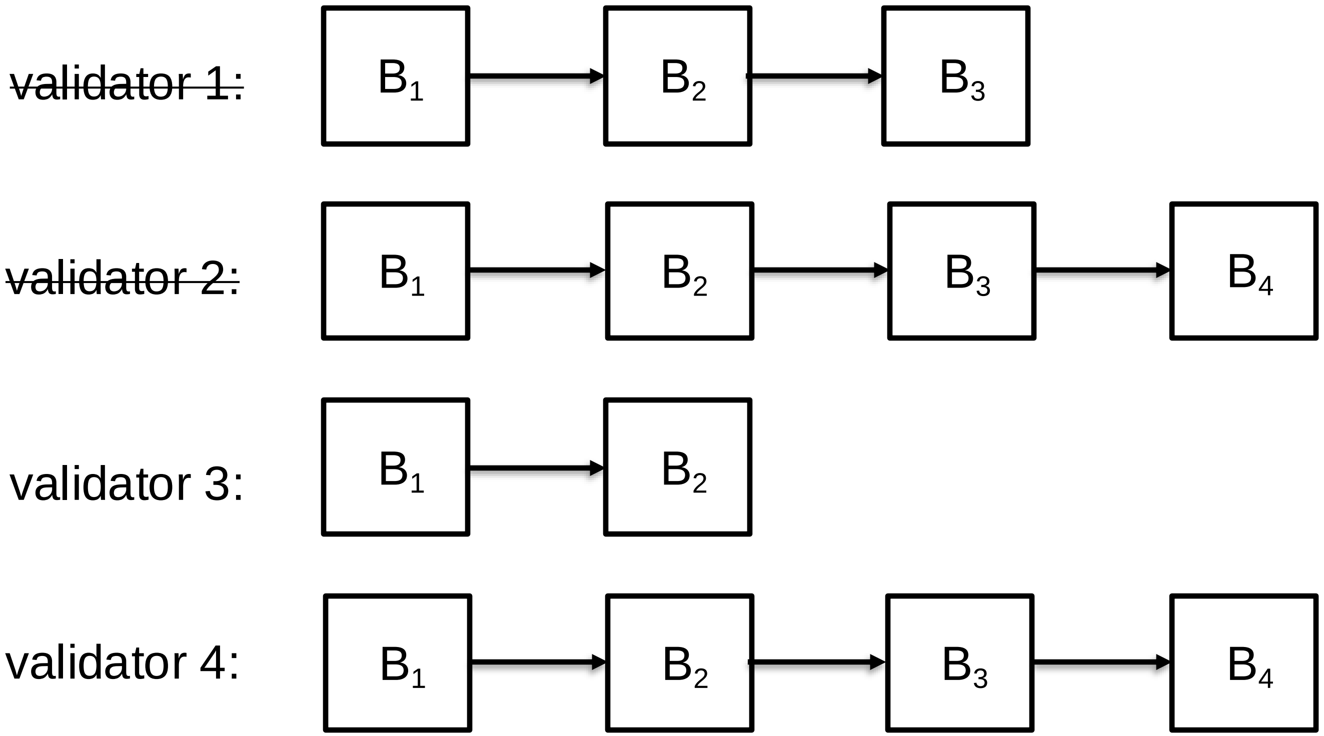

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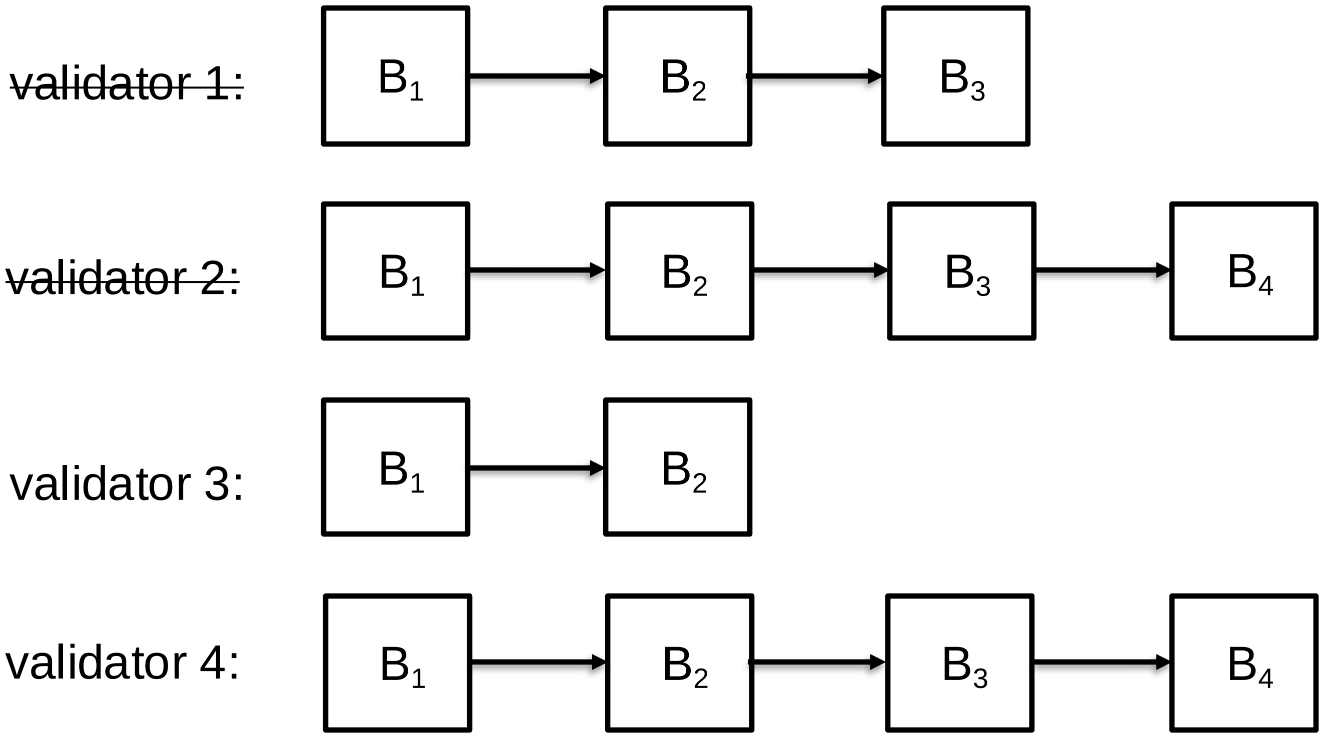

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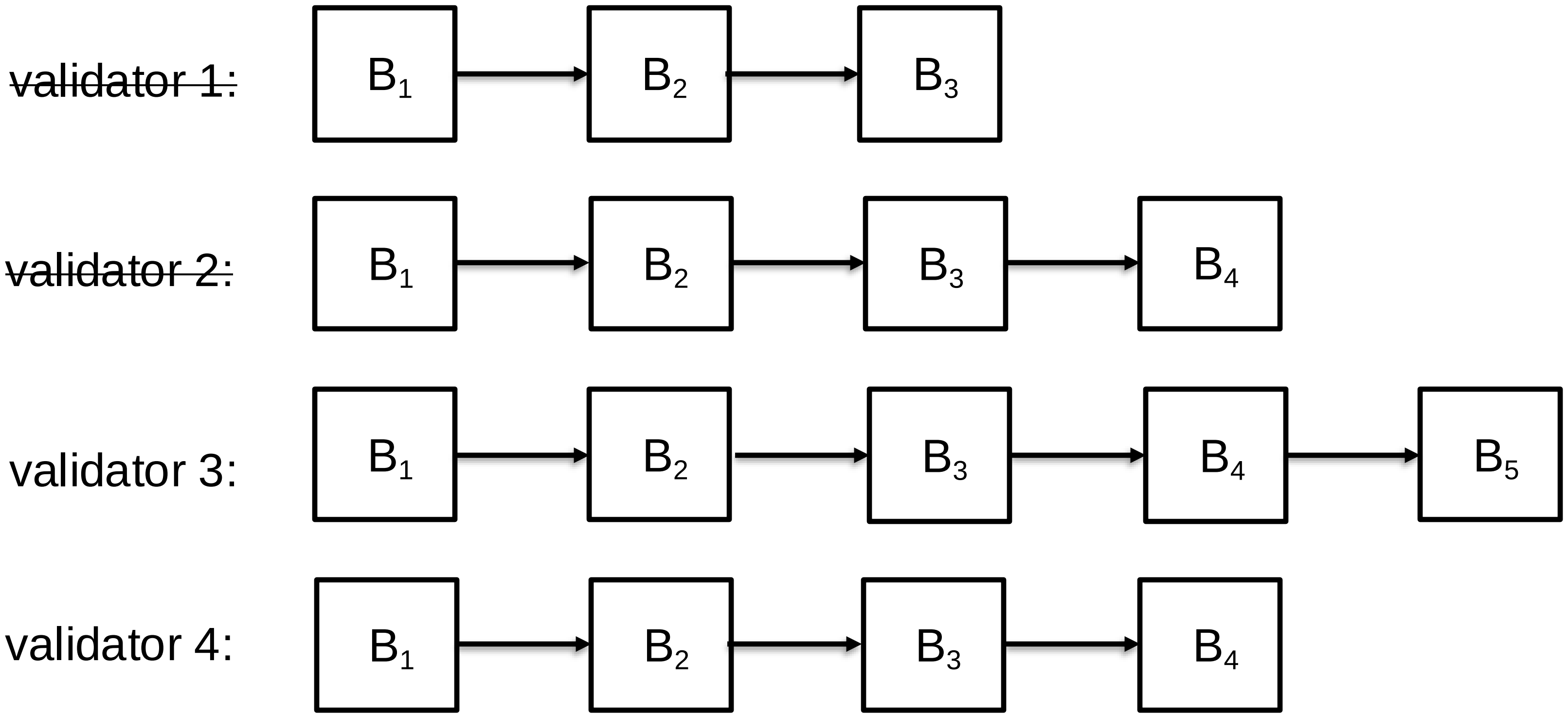

(validator 3 is next leader, prepares its proposal)

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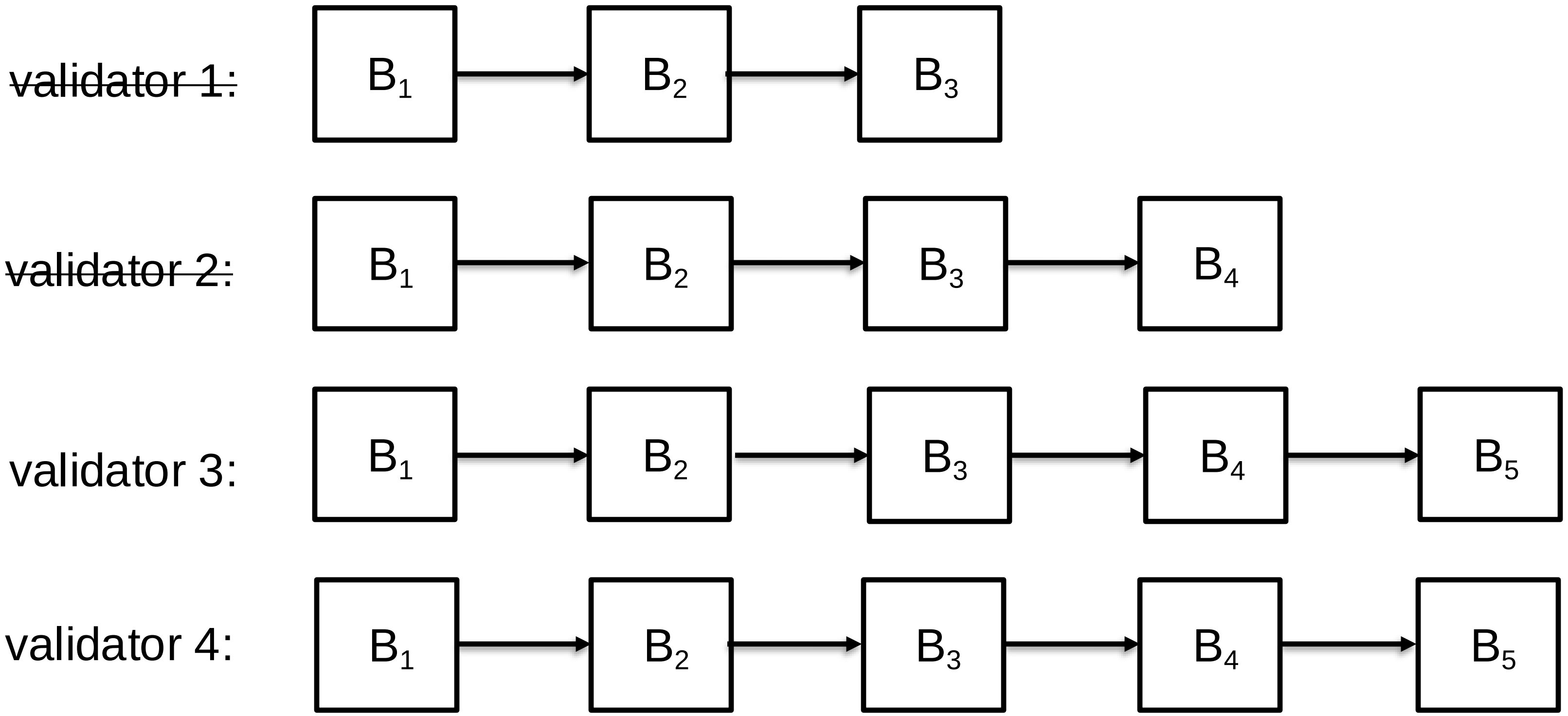

(if leader doesn't crash, all uncrashed validators adopt its proposal)

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- and bugs in a global consensus protocol likely to be exposed
  - run for multiple years under widely varying workloads/conditions

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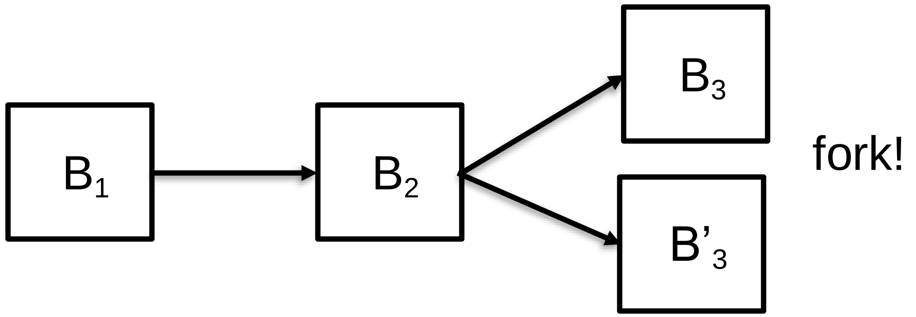

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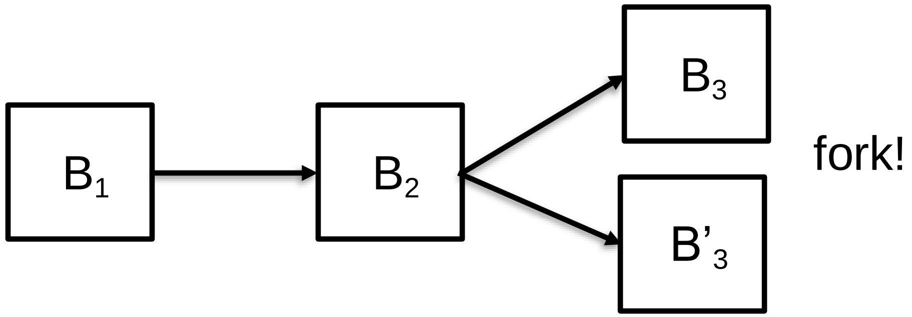

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- proceed by induction on the number of timesteps (true initially)
- in view v, by the inductive hypothesis, all the C_i's received by the leader are consistent (i.e., prefixes of a common chain)
  - these were the local chains of all not-yet-crashed validators at time $\Delta \cdot v$
  - leader receives all such C_i's by time $\Delta \cdot v + \Delta$ (due to synchrony)

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- C^* extends all these C_i's
- no matter which validators update their C_i's in this view, will stay consistent

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- C* adopted by all (uncrashed) validators

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   - 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

Takeaways/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!]

A Road Map to Practical SMR Protocols

crash faults +
synchronous network

crash faults +
asynchronous network

Byzantine faults +
asynchronous network

easier → harder

The Challenges of Asynchrony

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Key challenge: how to ensure leader knows about the C_i's of all non-faulty validators by the time it makes a proposal (despite unpredictable message delays)?

- – will resolve next lecture (add friction to proposing and to finalizing new transactions, also assume strict majority of non-faulty validators)

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FLP Theorem ('85): even with the threat of a single crash fault, can't solve SMR in the asynchronous model.

– see Friday bonus lecture for discussion and proof

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3. Use randomized protocols, solve SMR with high probability.
   – rich academic literature on this topic