# Production and Operations Management

## INFT 3611

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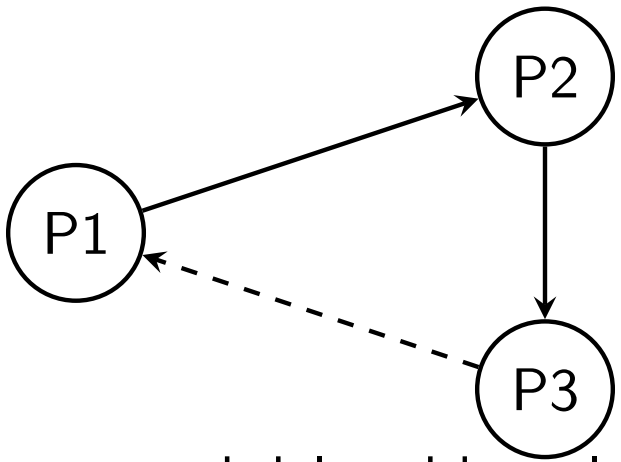
## Section 2: Architectures

***This content is based on the following public resources: https://www.distributed-systems.net/index.php/books/ds4/***

# Distributed Computation is Hard

## Problem

Distributed systems consist of independently executing processes that communicate over unreliable networks. Each process has only a partial, delayed, and inconsistent view of global state.




Different and delayed knowledge

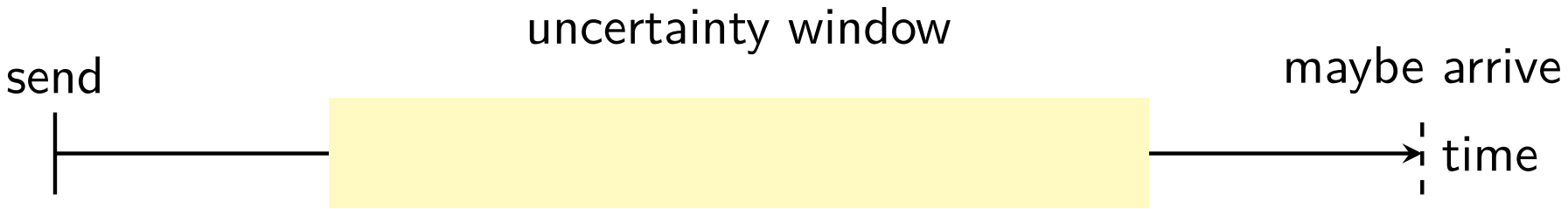
# Distributed Computation — Solutions

- **Logical clocks** for ordering without synchronized time.
- **Quorum-based decisions** instead of global agreement.
- **Replicated state machines** for deterministic consistency.
- **Retry and reconciliation** to overcome uncertainty.
- **Failure detectors** to approximate liveness information.

# Asynchrony

**Problem**

Message delays are unbounded. A node cannot distinguish a slow peer from a failed or partitioned one. Silence has no meaning.



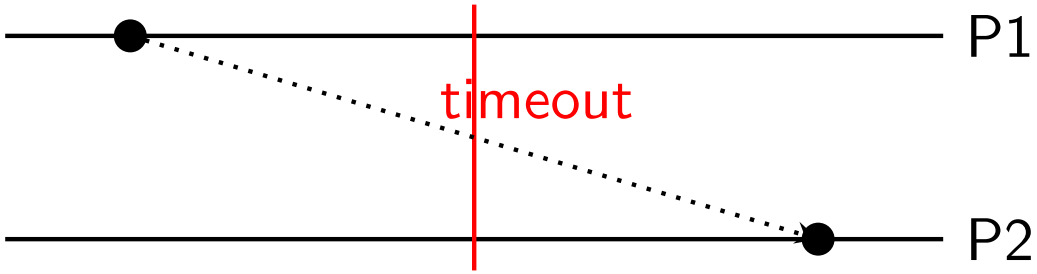
# Asynchrony — Solutions

- **Partial synchrony assumptions** for eventual timing bounds.
- **Randomized timeouts** to avoid synchronized failure.
- **Quorum reads/writes** to avoid waiting for all nodes.
- **Eventual failure detectors** that improve over time.
- **Logical ordering** instead of timing-based decisions.

# Timeout Ambiguity

## Problem

A timeout indicates missing messages, not a crash. Reacting prematurely can cause split-brain or two leaders if delayed messages later arrive.



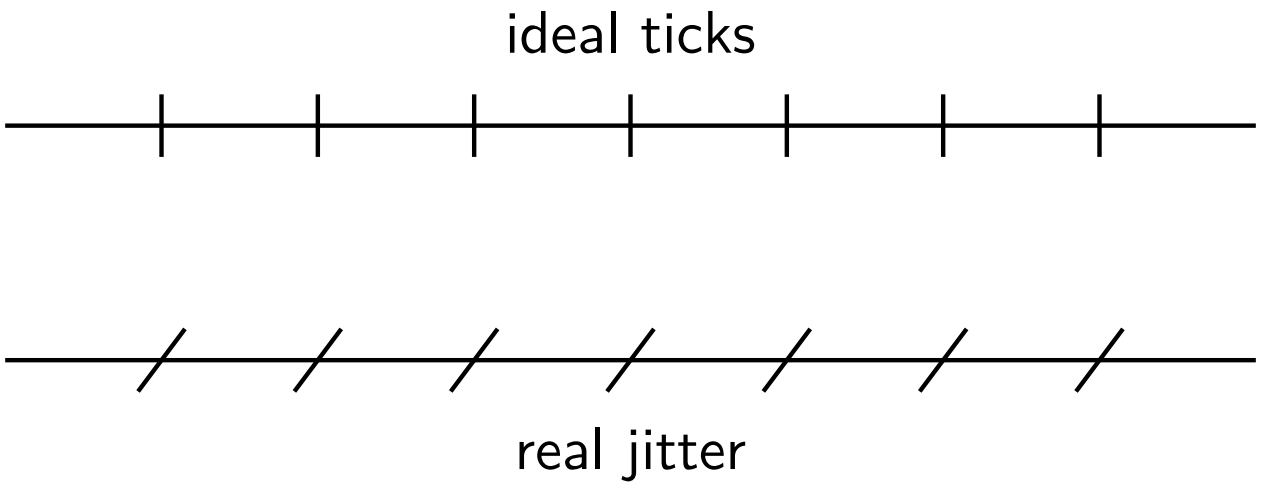
# Timeout Ambiguity — Solutions

- **Terms/epochs** invalidate outdated leaders (Raft).
- **Leases** provide time-bounded authority.
- **Commit rules** require quorum confirmation.
- **Redundant communication** to detect restored nodes.
- **Delayed leadership transition** to avoid flapping.

# Synchronous Model

## Problem

The synchronous model assumes predictable message and processing times. Real systems rarely meet these assumptions, causing synchronous algorithms to fail under modest delay.



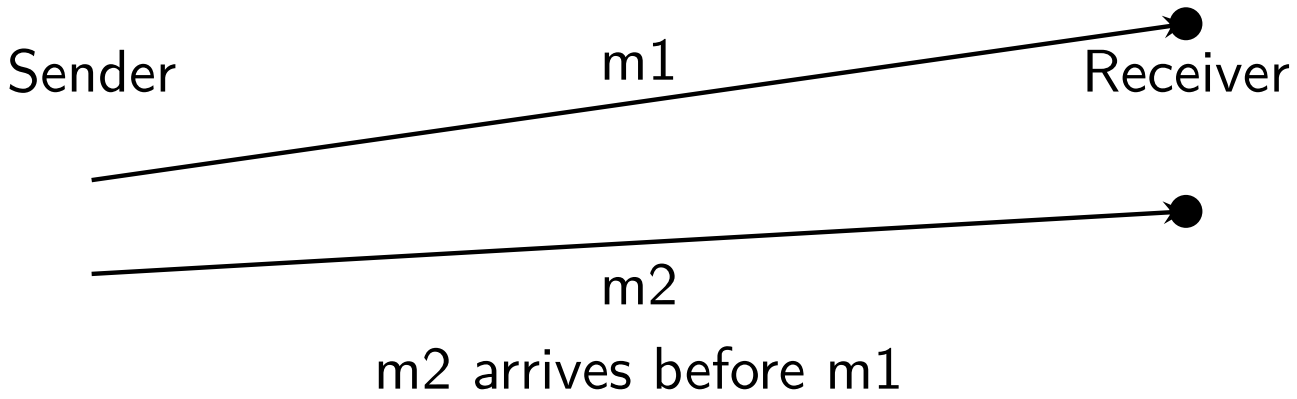
# Synchronous Model — Solutions

- **Treat synchrony as conceptual only**.
- **Design protocols for weaker models** (e.g., Raft, Paxos).
- **Avoid timing-based correctness assumptions**.
- **Use timeouts as hints, not proofs of failure**.
- **Use logical clocks** when real time is unreliable.

# Message Reordering

## Problem

Messages may traverse different network paths or face variable queueing delays. As a result, they can arrive in an order different from the one in which they were sent.



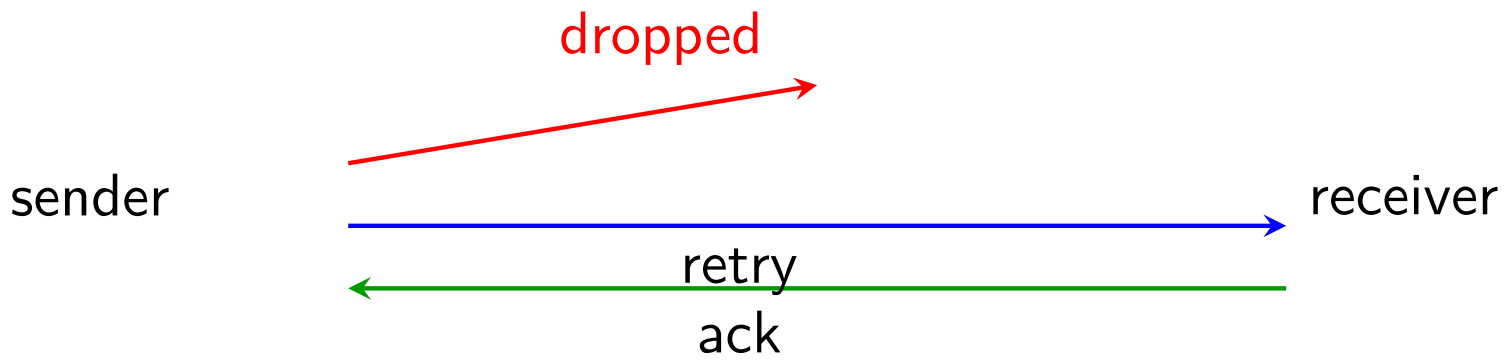
# Message Reordering — Solutions

- **Sequence numbers** to restore intended order.
- **Version vectors** to track causality across replicas.
- **Idempotent operations** to tolerate duplicates.
- **Deterministic replay** in replicated state machines.
- **Ordering layers** such as TCP or application-level queues.

# Message Loss

## Problem

Networks drop messages due to congestion, queue overflow, or transient link faults. Loss prevents updates from propagating and may leave replicas inconsistent.



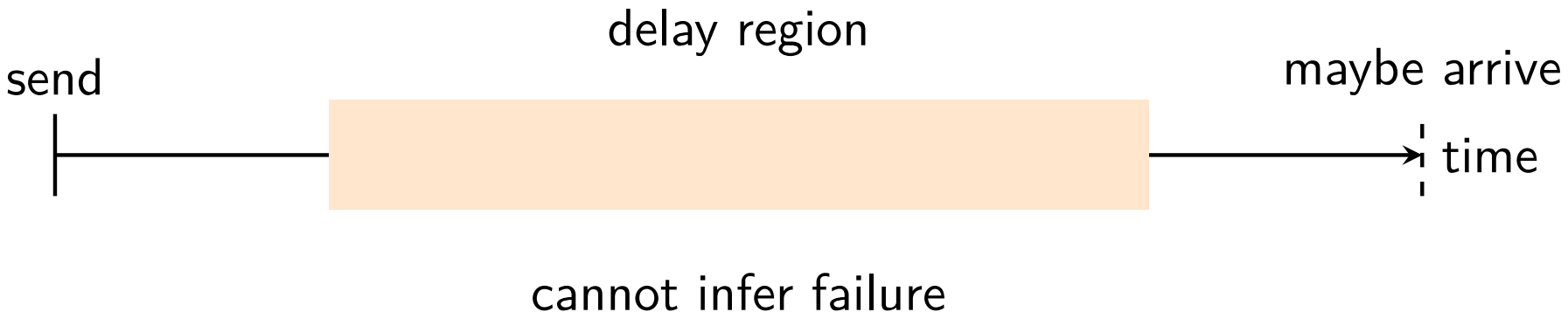
# Message Loss — Solutions

- **Retransmissions** until confirmation is received.
- **Acknowledgments** to confirm delivery.
- **Checksums** to detect corruption.
- **Backoff algorithms** to reduce congestion.
- **Periodic anti-entropy** to reconcile state.

# Arbitrary Delay

## Problem

Messages may be delayed indefinitely. Such delays look identical to failures, making timing unreliable for determining remote state or coordinating decisions.



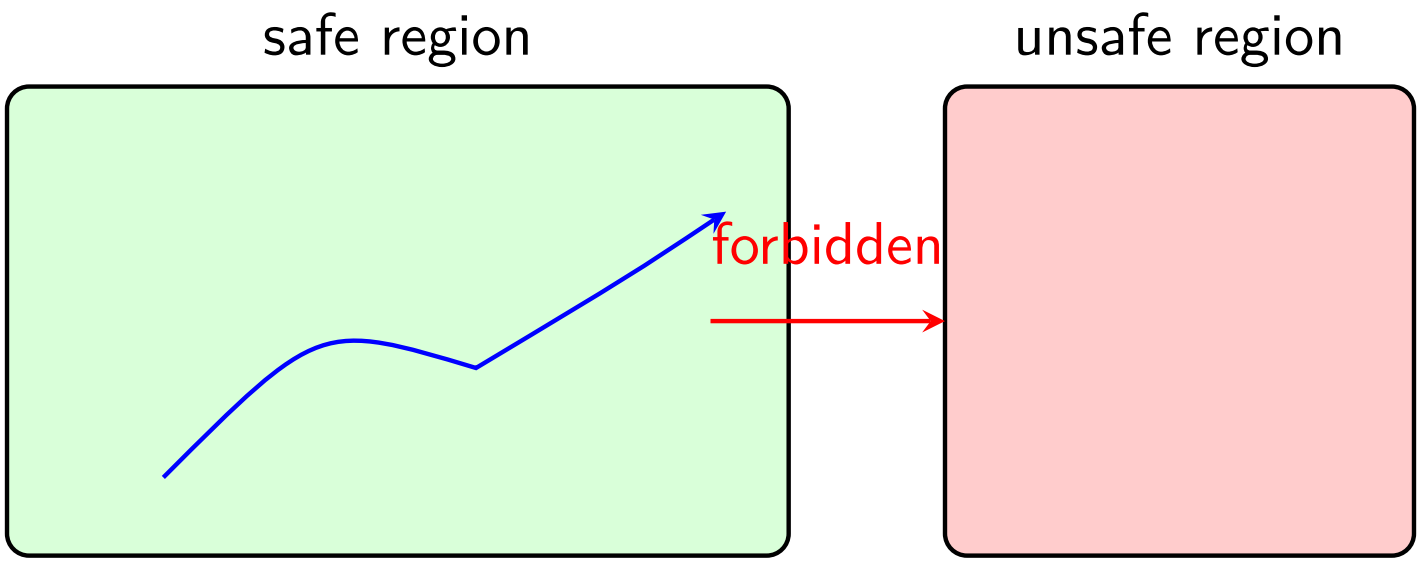
# Arbitrary Delay — Solutions

- **Quorum-based operations** to tolerate missing responses.
- **Randomized timeouts** to reduce coordination conflicts.
- **Eventually perfect failure detectors** improving over time.
- **Epoch-based leadership** to avoid split-brain.
- **Delay-independent safety rules** in consensus protocols.

# Safety

## Problem

A system violates safety if it reaches an invalid state—such as electing two leaders or committing conflicting operations. Safety violations cannot be undone once they occur.



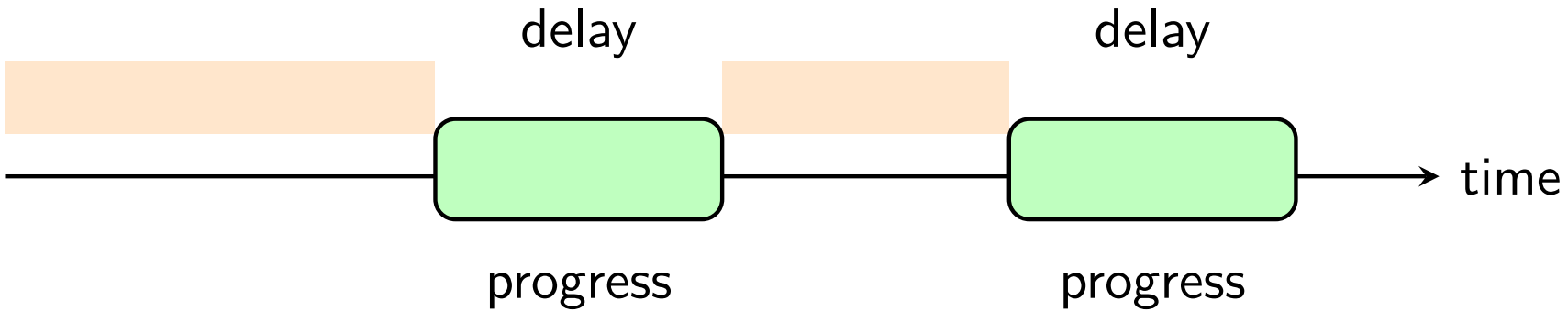
# Safety — Solutions

- **Single-writer leadership** to serialize decisions.
- **State machine replication** for deterministic behavior.
- **Quorum-based commits** to avoid conflicting decisions.
- **Monotonic state transitions** (legal state space).
- **Invariant-preserving protocols** such as Raft/Paxos.

# Liveness

## Problem

Even if safety holds, a system may stall indefinitely under heavy delay or unstable leadership. Liveness requires eventual forward progress.



# Liveness — Solutions

- **Randomized leader election** to break symmetry.
- **Eventually stable timeouts** after network recovery.
- **Retry loops** to ensure completion under partial failure.
- **Failure detectors** that improve accuracy over time.
- **Progress conditions** built into consensus protocols.

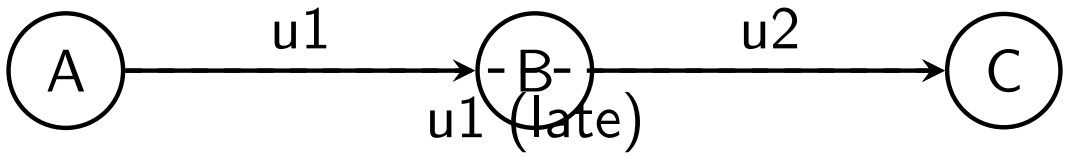
**Algorithm 1** Retry-with-Ack Protocol

```
1: send(msg)
2: while no ack received do
3:     wait(timeout)
4:     resend(msg)
5: end while
```

# Eventual Consistency

## Problem

Replicas receive updates in different orders and at different times. Without coordination, their states may temporarily diverge, producing inconsistent reads across the system.




temporary divergence

# Eventual Consistency — Solutions

- **Anti-entropy protocols** to exchange and reconcile state.
- **Version vectors** for detecting missing causal updates.
- **Idempotent updates** to tolerate replay and duplicates.
- **Convergent conflict-resolution rules** (e.g., LWW).
- **Periodic gossip** for reliable dissemination.

# Eventual Consistency — Anti-Entropy Algorithm

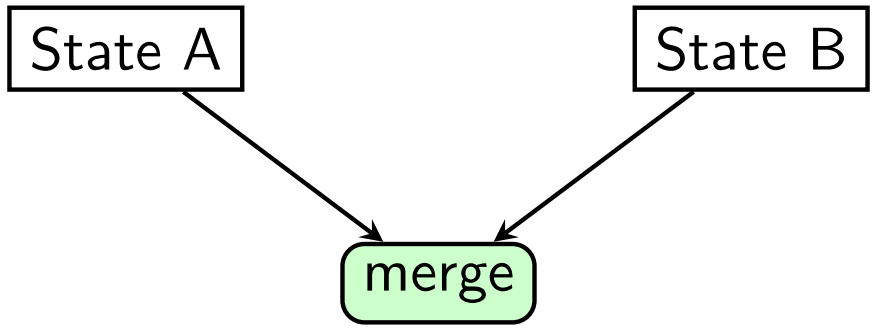
**Algorithm 2** Periodic Anti-Entropy

```
1: while true do
2:     wait(random_interval())
3:     peer ← pickRandomReplica()
4:     send(localState, peer)
5:     remoteState ← receive(peer)
6:     localState ← merge(localState, remoteState)
7: end while
```

# CRDT Convergence

## Problem

Conflict-free Replicated Data Types require carefully designed merge rules. Incorrect merge semantics or non-commutative operations can cause replicas to diverge permanently.




deterministic, convergent result

# CRDT Convergence — Solutions

- **Commutative updates** so order does not matter.
- **Associative merge operations** for consistent folding.
- **Idempotent merges** to handle duplicate state.
- **State-based CRDTs** for robust reconciliation.
- **Grow-only or monotonic structures** to avoid conflicts.

# CRDT — Version Vector Update Algorithm

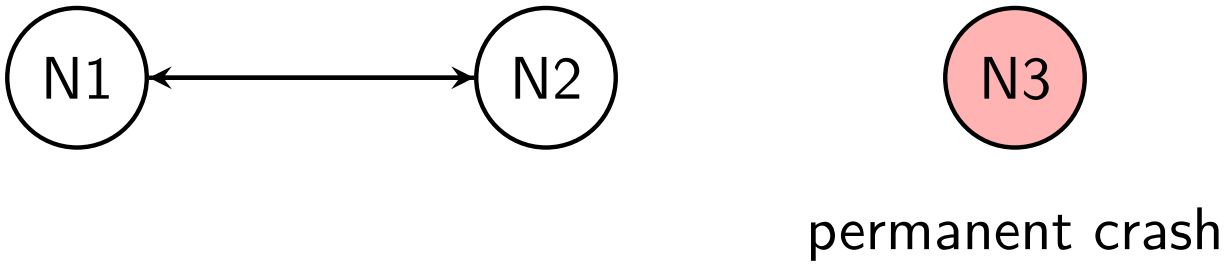
**Algorithm 3** Version Vector Update

```
1: vv[node] ← vv[node] + 1
2: attach(operation, vv)
3: broadcast(operation)
4: onReceive(op):
5:     vv[op.src] ← max(vv[op.src], op.vv[op.src])
6:     apply(op)
```

# Crash-Stop Failures

## Problem

Nodes may halt permanently due to hardware faults or power loss. They never recover or rejoin, reducing available replicas and risking loss of majority quorums.



# Crash-Stop — Solutions

- **Majority quorums** to tolerate permanent minority loss.
- **Replicated logs** to keep state despite node loss.
- **Leader re-election** to maintain progress.
- **Durable writes** that survive local crashes.
- **Static membership** for predictable fault tolerance.

# Crash-Recovery Log Reconstruction

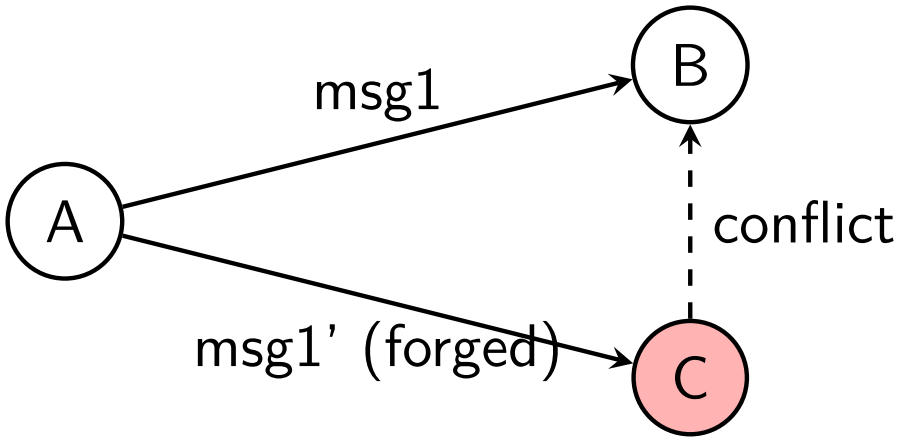
**Algorithm 4** Crash-Recovery Log Rebuild

```
1: onStartup():
2:     log ← loadFromDisk()
3:     lastIndex ← log.tail
4:     send(hello, peers)
5:     missing ← fetchEntries(lastIndex, peers)
6:     append(log, missing)
7:     restoreState(log)
```

# Byzantine Failures

## Problem

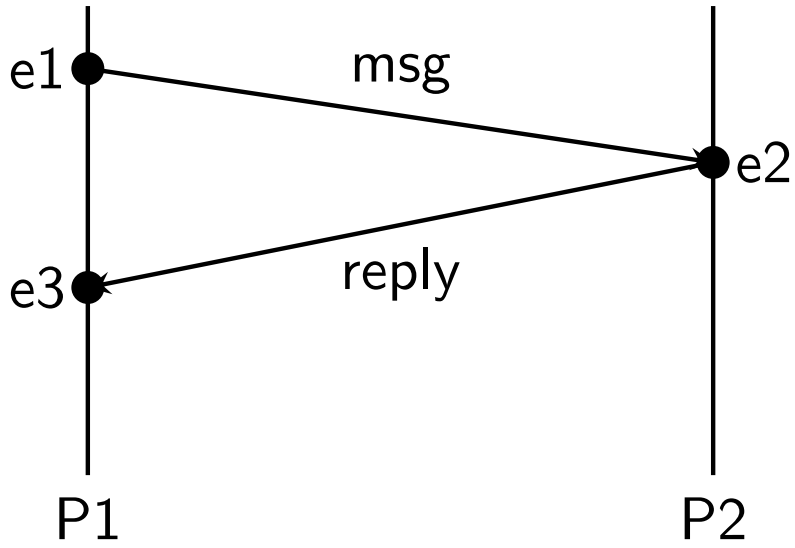
Nodes may behave arbitrarily: forging messages, equivocating, or selectively dropping updates. This breaks assumptions in non-Byzantine protocols and can mislead peers.



# Lamport Clocks

## Problem

Without synchronized clocks, processes cannot agree on the order of events using physical time. Concurrent events make real-time ordering ambiguous.



# Lamport Clocks — Solutions

- **Monotonic counters** incremented on each event.
- **Piggyback timestamps** on every message.
- **Max-merge rule** to update local clocks.
- **Defines happens-before** without physical time.
- **Total order** via tie-breaking with process ID.

# Lamport Clock Update Algorithm

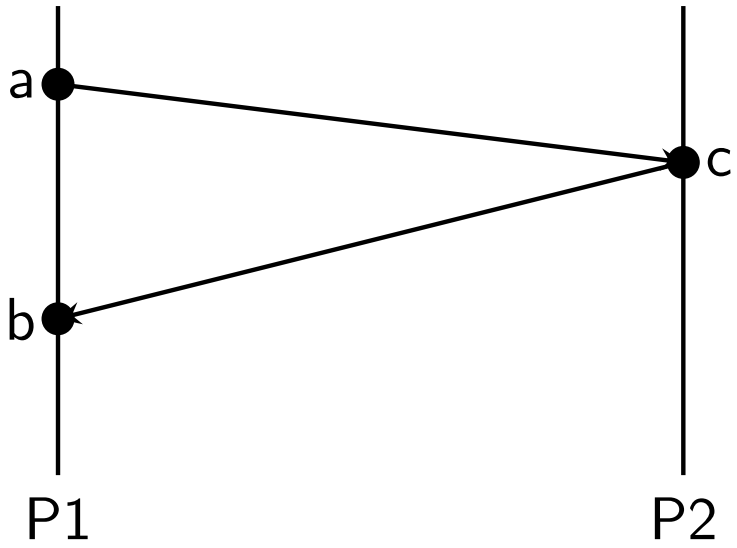
**Algorithm 5** Lamport Timestamp Update

```
1: onLocalEvent():
2:         clock ← clock + 1
3: onSend(msg):
4:         clock ← clock + 1
5:         msg.ts ← clock
6:         send(msg)
7: onReceive(msg):
8:         clock ← max(clock, msg.ts) + 1
```

# Happens-Before Relation

## Problem

Determining causality between events is difficult without a global timeline. Concurrent events appear unordered in real time.



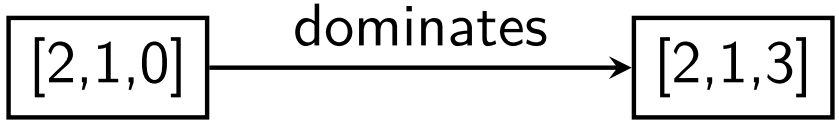
# Happens-Before — Solutions

- **Lamport timestamps** encode causal precedence.
- **HB defines concurrency** when neither event dominates.
- **Prevents reordering errors** in replicated logs.
- **Supports deterministic replay**.
- **Enables causal consistency** across replicas.

# Vector Clocks

**Problem**

Lamport clocks cannot distinguish true concurrency from causality. Systems require richer metadata to track causality accurately.




componentwise comparison

# Vector Clocks — Solutions

- **Track causality** per process dimension.
- **Detect concurrency** using vector comparison rules.
- **Support multi-writer replication**.
- **Drive conflict resolution** in CRDTs.
- **Minimal metadata** for consistent ordering.

# Vector Clock Update Algorithm

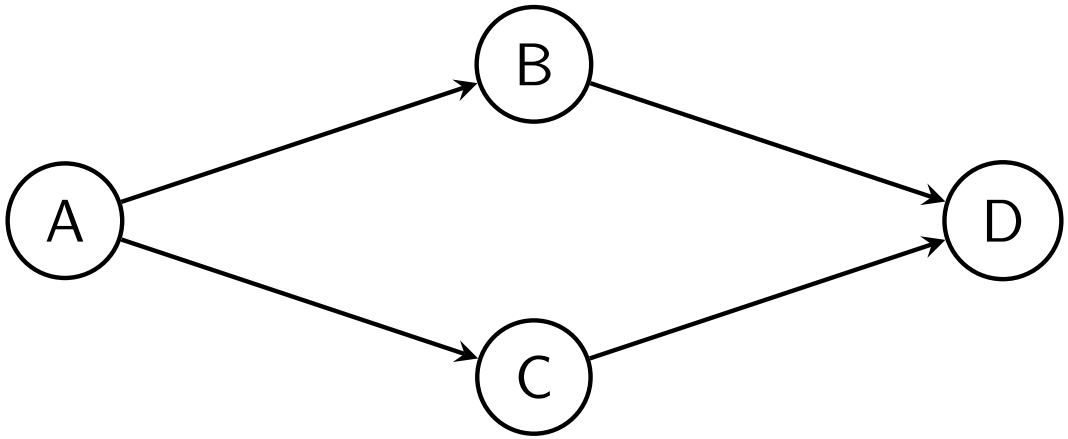
**Algorithm 6** Vector Clock Update

```
1:  onLocalEvent():
2:        VC[i] ← VC[i] + 1
3:  onSend(op):
4:        VC[i] ← VC[i] + 1
5:        op.VC ← VC
6:  onReceive(op):
7:
8:  for each process j do
9:                  VC[j] ← max(VC[j], op.VC[j])
10: end for
11:       VC[i] ← VC[i] + 1
```

# Gossip Dissemination

## Problem

Broadcasting updates reliably in large clusters is expensive. Loss or delays slow convergence if updates aren't propagated probabilistically.




multi-step, probabilistic spreading

# Gossip — Solutions

- **Random peer selection** to avoid bottlenecks.
- **Push-pull exchange** to accelerate convergence.
- **Periodic rounds** for steady dissemination.
- **Rumor-mongering** to limit message load.
- **Epidemic-style propagation** for scalability.

# Gossip Round Algorithm

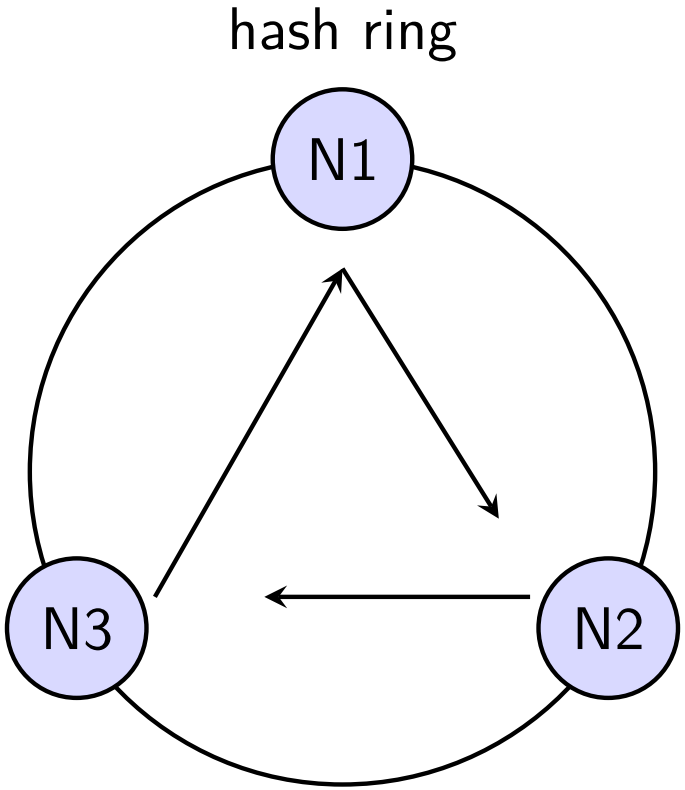
**Algorithm 7** Push-Pull Gossip

```
1: while true do
2:     wait(roundInterval)
3:     peer ← pickRandom()
4:     send(localState, peer)
5:     remote ← receive(peer)
6:     localState ← merge(localState, remote)
7: end while
```

# Consistent Hashing

## Problem

When nodes join or leave, naive sharding causes large-scale data movement. Systems need key distribution that minimizes redistribution.

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