Distributed Systems (COMP9243)

Lecture 5: Synchronisation and Coordination

(Part 2)

① Transactions

② Elections

③ Multicast

Transactions

TRANSACTIONS

Transaction:

- Comes from database world
- Defines a sequence of operations
- Atomic in presence of multiple clients and failures

Mutual Exclusion ++:

- Protect shared data against simultaneous access
- Allow multiple data items to be modified in single atomic action

Transaction Model:

Operations:

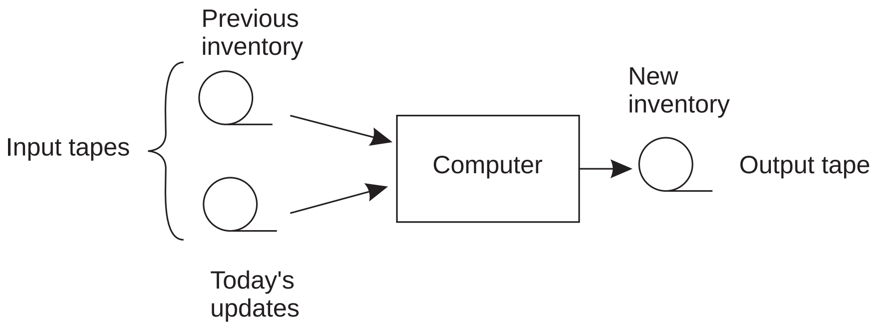
- `BeginTransaction`
- `EndTransaction`
- `Read`
- `Write`

End of Transaction:

- Commit
- Abort

Transaction Examples

Inventory:



Banking:

```
BeginTransaction
   b = A.Balance();
   A.Withdraw(b);
   B.Deposit(b);
EndTransaction
```

ACID PROPERTIES

atomic: all-or-nothing. once committed the full transaction is performed, if aborted, there is no trace left;

consistent: the transaction does not violate system invariants (i.e. it does not produce inconsistent results)

isolated: transactions do not interfere with each other i.e. no intermediate state of a transaction is visible outside (also called serialisable);

durable: after a commit, results are permanent (even if server or hardware fails)

Classification of Transactions

Flat: sequence of operations that satisfies ACID

Nested: *hierarchy* of transactions

Distributed: (flat) transaction that is executed on distributed data

Flat Transactions:

- ✓ Simple
- ✗ Failure → all changes undone

```
BeginTransaction
  accountA -= 100;
  accountB += 50;
  accountC += 25;
  accountD += 25;
EndTransaction
```

Nested Transaction

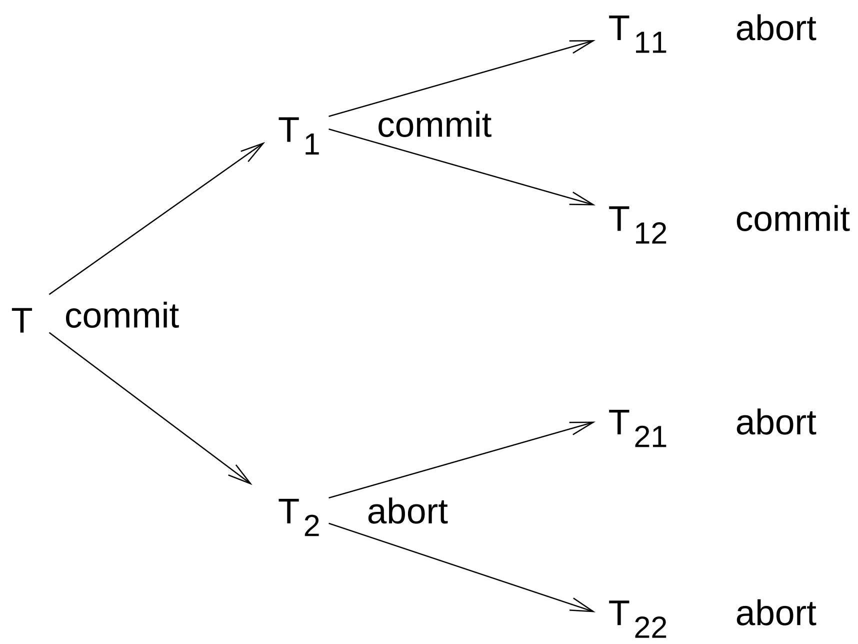
Example:

Booking a flight

- ☑ Sydney → Manila
- ☑ Manila → Amsterdam
- ☒ Amsterdam → Toronto

What to do?

- ➜ Abort whole transaction
- ➜ Commit nonaborted parts of transaction only
- ➜ Partially commit transaction and try alternative for aborted part



- *Subtransactions* and parent transactions
- Parent transaction may commit even if some subtransactions aborted
- Parent transaction aborts $\rightarrow$ all subtransactions abort

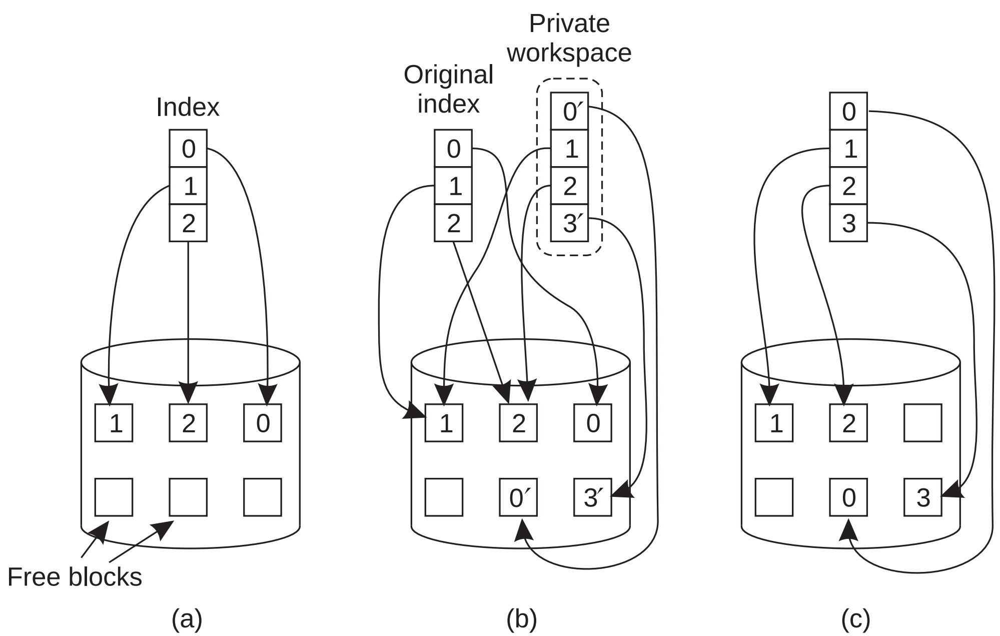
Subtransactions:

- ➜ Subtransaction can abort any time
- ➜ Subtransaction cannot commit until parent ready to commit
  - Subtransaction either aborts or commits provisionally
  - Provisionally committed subtransaction reports provisional commit list, containing all its provisionally committed subtransactions, to parent
  - On commit, all subtransaction in that list are committed
  - On abort, all subtransactions in that list are aborted.

Transaction Atomicity Implementation

Private Workspace:

- ➜ Perform all *tentative* operations on a *shadow copy*
- ➜ Atomically swap with main copy on `Commit`
- ➜ Discard shadow on `Abort`.



Writeahead Log:

- ➜ In-place update with writeahead logging
- ➜ Roll back on `Abort`

```
x = 0;
y = 0;
BEGIN_TRANSACTION;
    x = x + 1;
    y = y + 2;
    x = y * y;
END_TRANSACTION;
```
(a)

Log	Log	Log
[x = 0/1]	[x = 0/1]	[x = 0/1]
	[y = 0/2]	[y = 0/2]
		[x = 1/4]
(b)	(c)	(d)

Concurrency Control (Isolation)

Simultaneous Transactions:

- ➜ Clients accessing bank accounts
- ➜ Travel agents booking flights
- ➜ Inventory system updated by cash registers

Problems:

- ➜ Simultaneous transactions may interfere
  - Lost update
  - Inconsistent retrieval
- ➜ Consistency and Isolation require that there is no interference
  Why?

Concurrency Control Algorithms:

- ➜ Guarantee that multiple transactions can be executed simultaneously while still being isolated.
- ➜ As though transactions executed one after another

CONFLICTS AND SERIALISABILITY

Read/Write Conflicts Revisited:

conflict: operations (from the same, or different transactions) that operate on same data

read-write conflict: one of the operations is a write

write-write conflict: more than one operation is a write

Schedule:

➜ Total ordering (interleaving) of operations

➜ Legal schedules provide results as though transactions serialised (*serial equivalence*)

Example Schedules:

```
BEGIN_TRANSACTION
   x = 0;
   x = x + 1;
END_TRANSACTION
```

(a)

```
BEGIN_TRANSACTION
   x = 0;
   x = x + 2;
END_TRANSACTION
```

(b)

```
BEGIN_TRANSACTION
   x = 0;
   x = x + 3;
END_TRANSACTION
```

(c)

Time →

Schedule 1	x = 0;	x = x + 1;	x = 0;	x = x + 2;	x = 0;	x = x + 3;	Legal
Schedule 2	x = 0;	x = 0;	x = x + 1;	x = x + 2;	x = 0;	x = x + 3;	Legal
Schedule 3	x = 0;	x = 0;	x = x + 1;	x = 0;	x = x + 2;	x = x + 3;	Illegal

(d)

Serialisable Execution

Serial Equivalence:

➜ conflicting operations performed in same order on all data items

- operation in T_1 before T_2, or
- operation in T_2 before T_1

Are the following serially equivalent?

➜ $R_1(x)W_1(x)R_2(y)W_2(y)R_2(x)W_1(y)$

➜ $R_1(x)R_2(y)W_2(y)R_2(x)W_1(x)W_1(y)$

➜ $R_1(x)R_2(x)W_1(x)W_2(y)R_2(y)W_1(y)$

➜ $R_1(x)W_1(x)R_2(x)W_2(y)R_2(y)W_1(y)$

Managing Concurrency

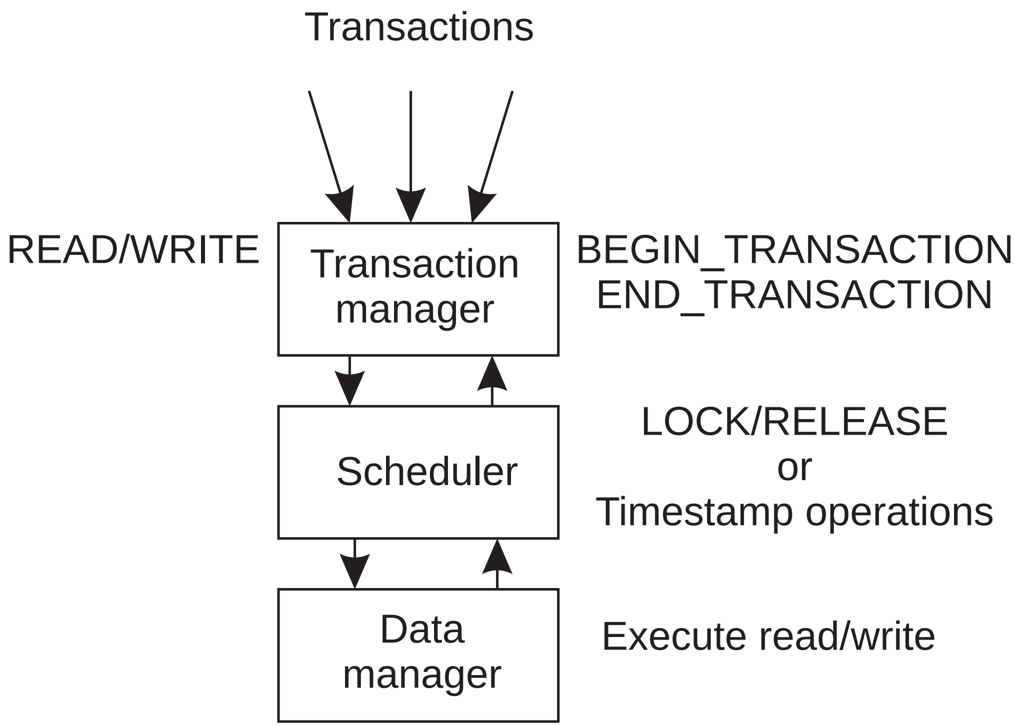
Dealing with Concurrency:

➜ Locking

➜ Timestamp Ordering

➜ Optimistic Control

Transaction Managers:

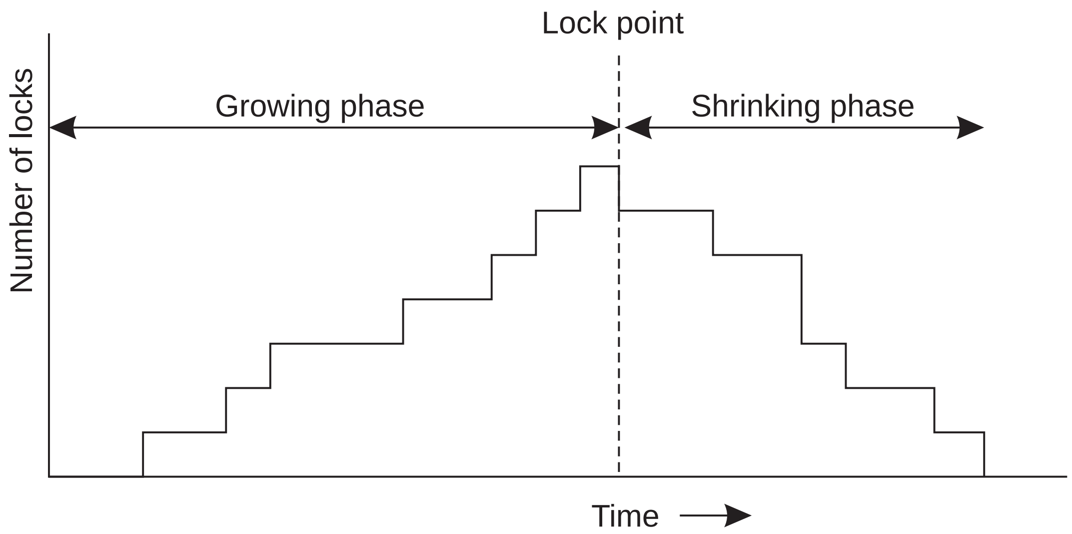


LOCKING

Pessimistic approach: prevent illegal schedules

- ➜ Lock must be obtained from scheduler before a read or write.
- ➜ Scheduler grants and releases locks
- ➜ Ensures that only valid schedules result

Two Phase Locking (2PL)



① Lock granted if no conflicting locks on that data item. Otherwise operation delayed until lock released.

② Lock is not released until operation executed by data manager

③ No more locks granted after a release has taken place

All schedules formed using 2PL are serialisable.

PROBLEMS WITH LOCKING

Deadlock:

- ➜ Detect and break deadlocks (in scheduler)
- ➜ Timeout on locks

Cascaded Aborts:

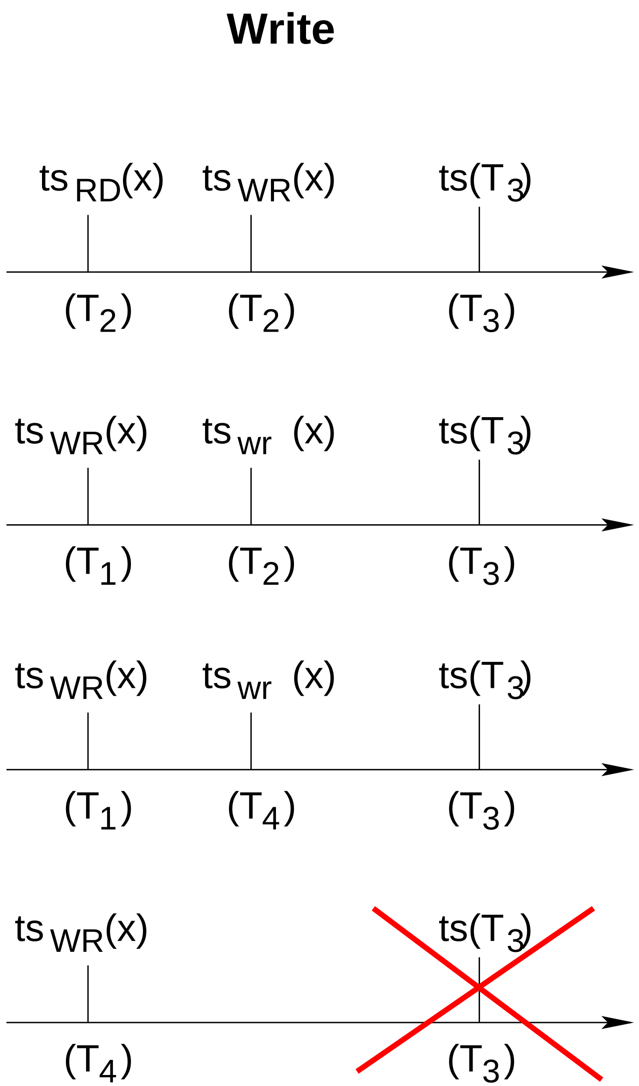
- ➜ $Release(T_i, x) \rightarrow Lock(T_j, x) \rightarrow Abort(T_i)$
- ➜ T_j will have to be aborted too
- ➜ Problem: dirty read: seen value from non-committed transaction

solution: Strict Two-Phase Locking:

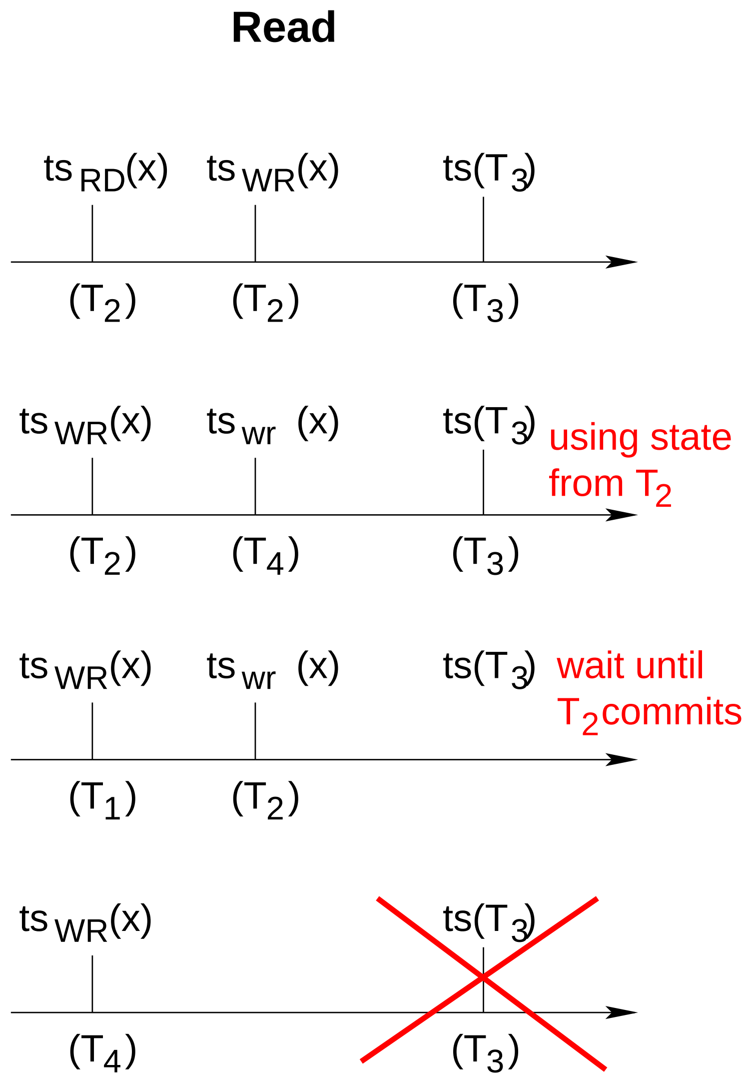
- ➜ Release *all* locks at `Commit/Abort`

Timestamp Ordering

- Each transaction has unique timestamp ($ts(T_i)$)
- Each operation ($TS(W)$, $TS(R)$) receives its transaction's timestamp
- Each data item has two timestamps:
  - read timestamp: $ts_{RD}(x)$ - transaction that most recently read x
  - write timestamp: $ts_{WR}(x)$ - committed transaction that most recently wrote x
- Also tentative write timestamps (noncommitted writes) $ts_{wr}(x)$
- Timestamp ordering rule:
  - write request only valid if $TS(W) > ts_{WR}$ and $TS(W) \geq ts_{RD}$
  - read request only valid if $TS(R) > ts_{WR}$
- Conflict resolution:
  - Operation with lower timestamp executed first



Write
ts RD(x) ts WR(x) ts(T3)
(T2) (T2) (T3)
ts WR(x) ts wr (x) ts(T3)
(T1) (T2) (T3)
ts WR(x) ts wr (x) ts(T3)
(T1) (T4) (T3)
ts WR(x) ts(T3)
(T4) (T3)



Read
ts RD(x) ts WR(x) ts(T3)
(T2) (T2) (T3)
ts WR(x) ts wr (x) ts(T3)
using state from T2
(T2) (T4) (T3)
ts WR(x) ts wr (x) ts(T3)
wait until T2 commits
(T1) (T2)
ts WR(x) ts(T3)
(T4) (T3)

Optimistic Control

Assume that no conflicts will occur.

➜ Detect conflicts at commit time

➜ Three phases:

- Working (using shadow copies)
- Validation
- Update

Validation:

- ➜ Keep track of read set and write set during working phase
- ➜ During validation make sure conflicting operations with *overlapping* transactions are serialisable
  - Make sure T_v doesn't read items written by other T_is Why?
  - Make sure T_v doesn't write items read by other T_is Why?
  - Make sure T_v doesn't write items written by other T_is Why?
- ➜ Prevent overlapping of validation phases (mutual exclusion)

Backward validation:

- ➜ Check committed overlapping transactions
- ➜ Only have to check if T_v read something another T_i has written
- ➜ Abort T_v if conflict
  - ✗ Have to keep old write sets

Forward validation:

- ➜ Check not yet committed overlapping transactions
- ➜ Only have to check if T_v wrote something another T_i has read
- ➜ Options on conflict: abort T_v, abort T_i, wait
  - ✗ Read sets of not yet committed transactions may change during validation!

Distributed Transactions

➜ In distributed system, a single transaction will, in general, involve several servers:

- transaction may require several services,
- transaction involves files stored on different servers

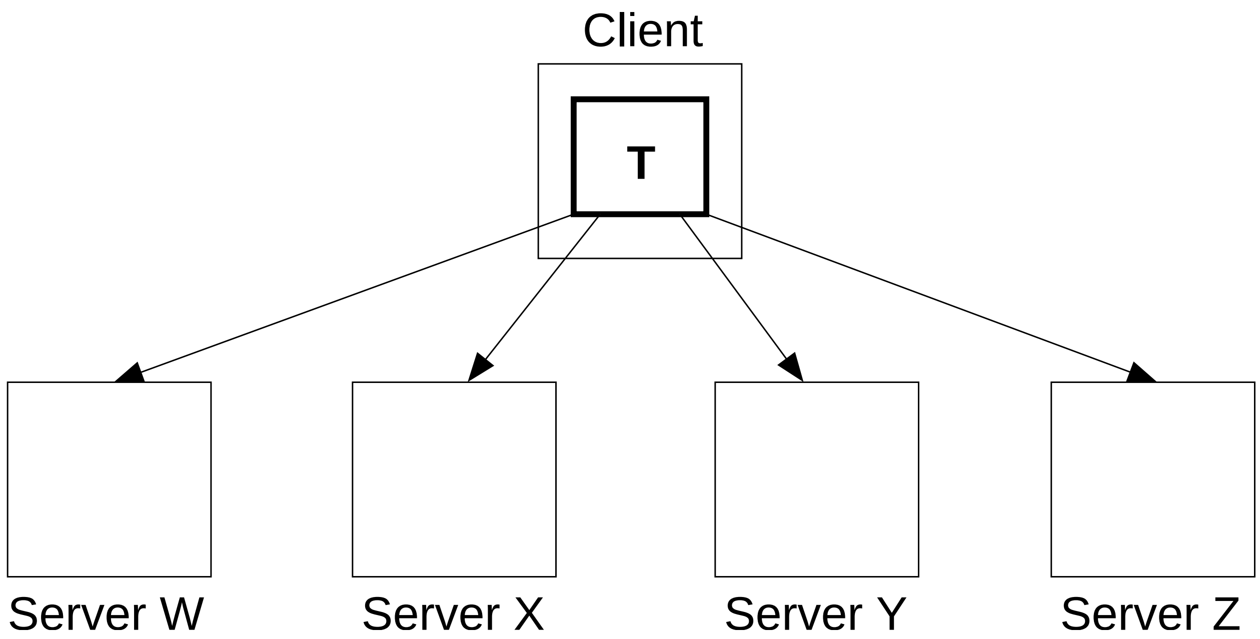
➜ All servers must agree to *Commit* or *Abort*, and do this atomically.

Transaction Management:

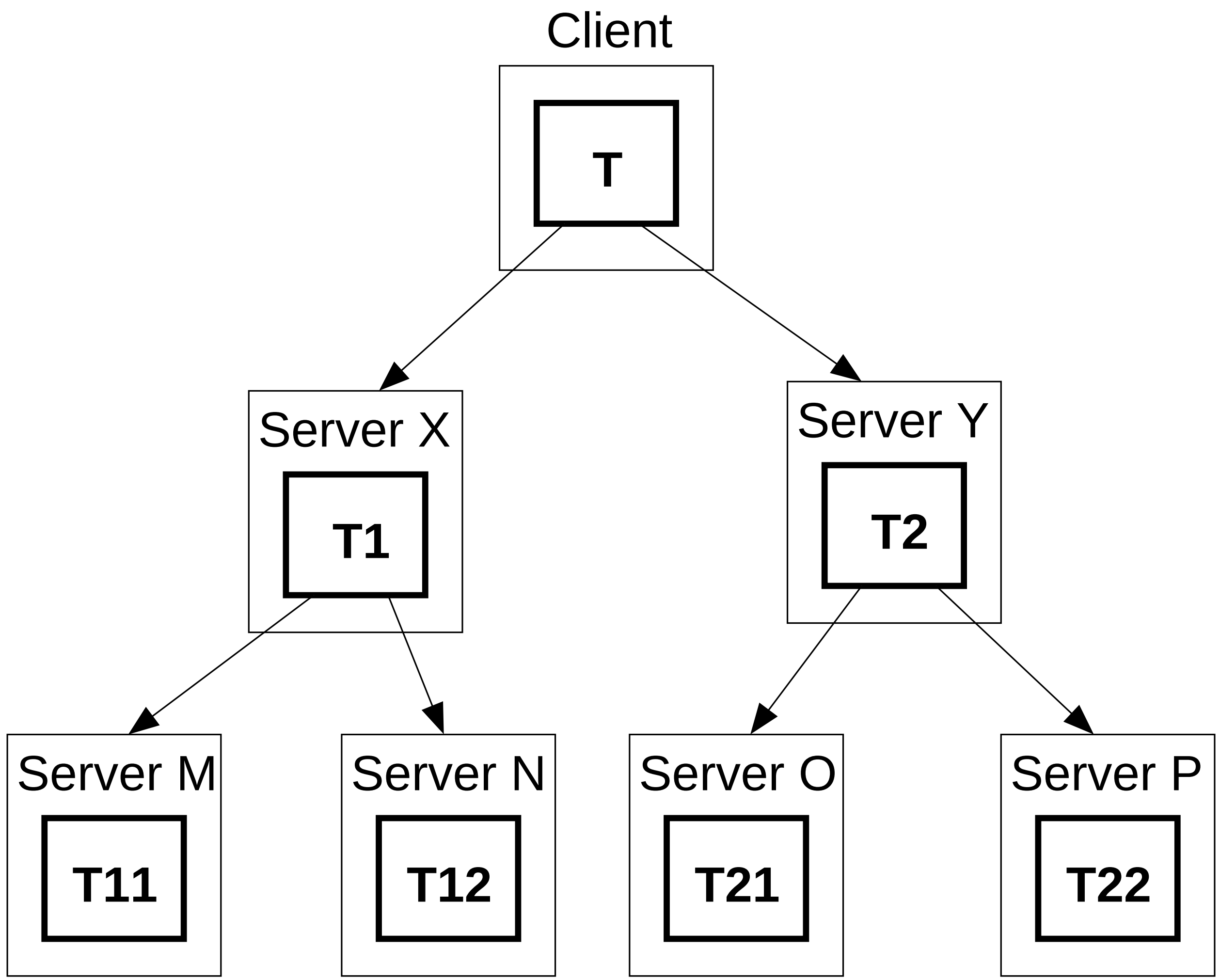
➜ Centralised

➜ Distributed

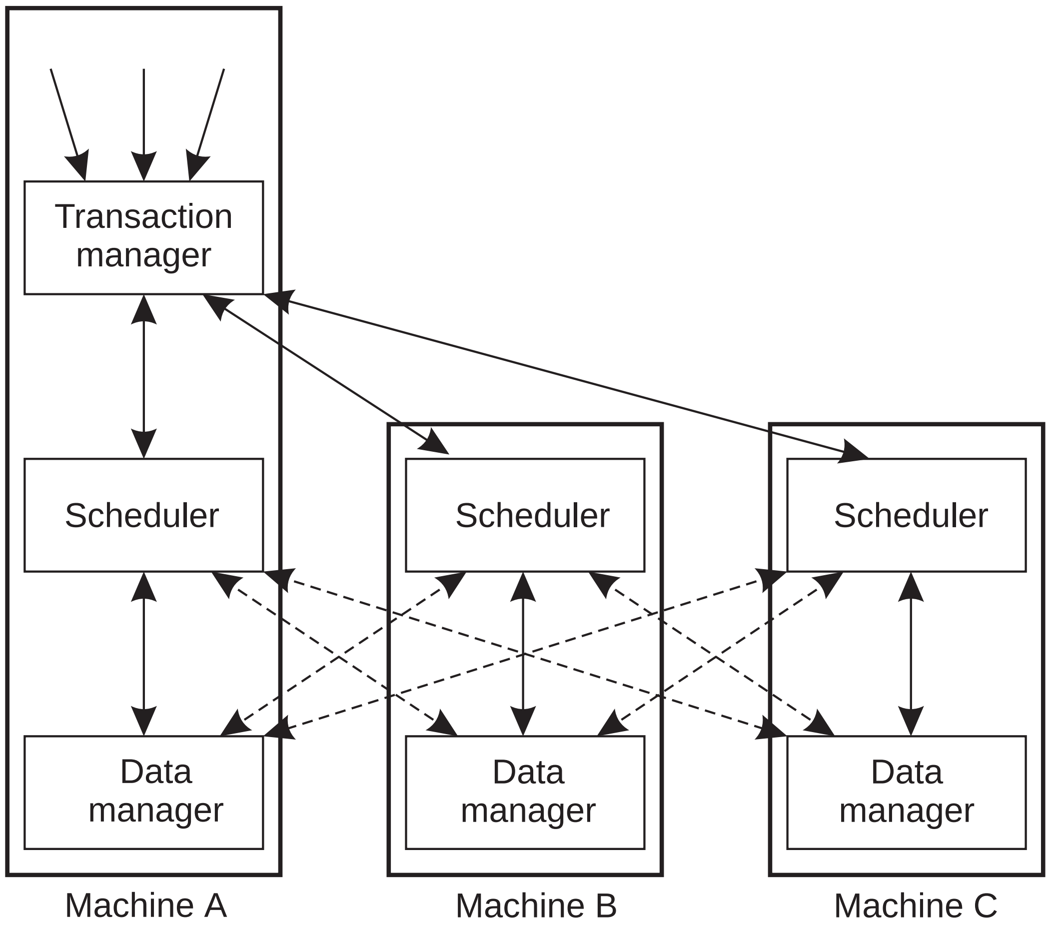
Distributed Flat Transaction:



Distributed Nested Transaction:



Distributed Concurrency Control



Distributed Locking

Centralised 2PL:

- ➜ Single server handles all locks
- ➜ Scheduler only grants locks, transaction manager contacts data manager for operation.

Primary 2PL:

- ➜ Each data item is assigned a primary copy
- ➜ Scheduler on that server responsible for locks

Distributed 2PL:

- ➜ Data can be replicated
- ➜ Scheduler on each machine responsible for locking own data
- ➜ Read lock: contact any replica
- ➜ Write lock: contact all replicas

Distributed Timestamps:

Assigning unique timestamps:

- ➜ Timestamp assigned by first scheduler accessed
- ➜ Clocks have to be roughly synchronized

Distributed Optimistic Control:

- ➜ Validation operations distributed over servers
- ➜ Commitment deadlock (because of mutual exclusion of validation)
- ➜ Parallel validation protocol
- ➜ Make sure that transaction serialised correctly

Atomicity and Distributed Transactions

Distributed Transaction Organisation:

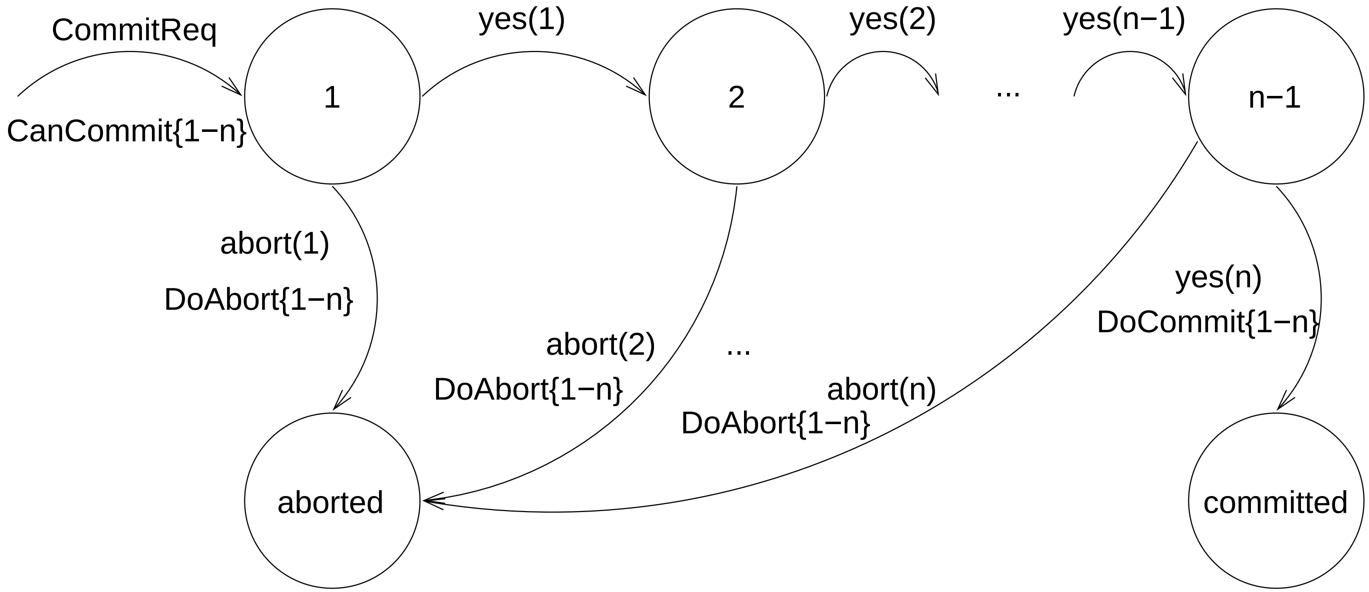
- ➜ Each distributed transaction has a coordinator, the server handling the initial `BeginTransaction` call
- ➜ Coordinator maintains a list of workers, i.e. other servers involved in the transaction
- ➜ Each worker needs to know coordinator
- ➜ Coordinator is responsible for ensuring that whole transaction is atomically committed or aborted
  - ➻ Require a distributed commit protocol.

Distributed atomic commit

- ➜ Transaction may only be able to commit when all workers are ready to commit (e.g. validation in optimistic concurrency)
- ➜ Hence distributed commit requires at least two phases:
  1. **Voting phase:** all workers vote on commit, coordinator then decides whether to commit or abort.
  2. **Completion phase:** all workers commit or abort according to decision.

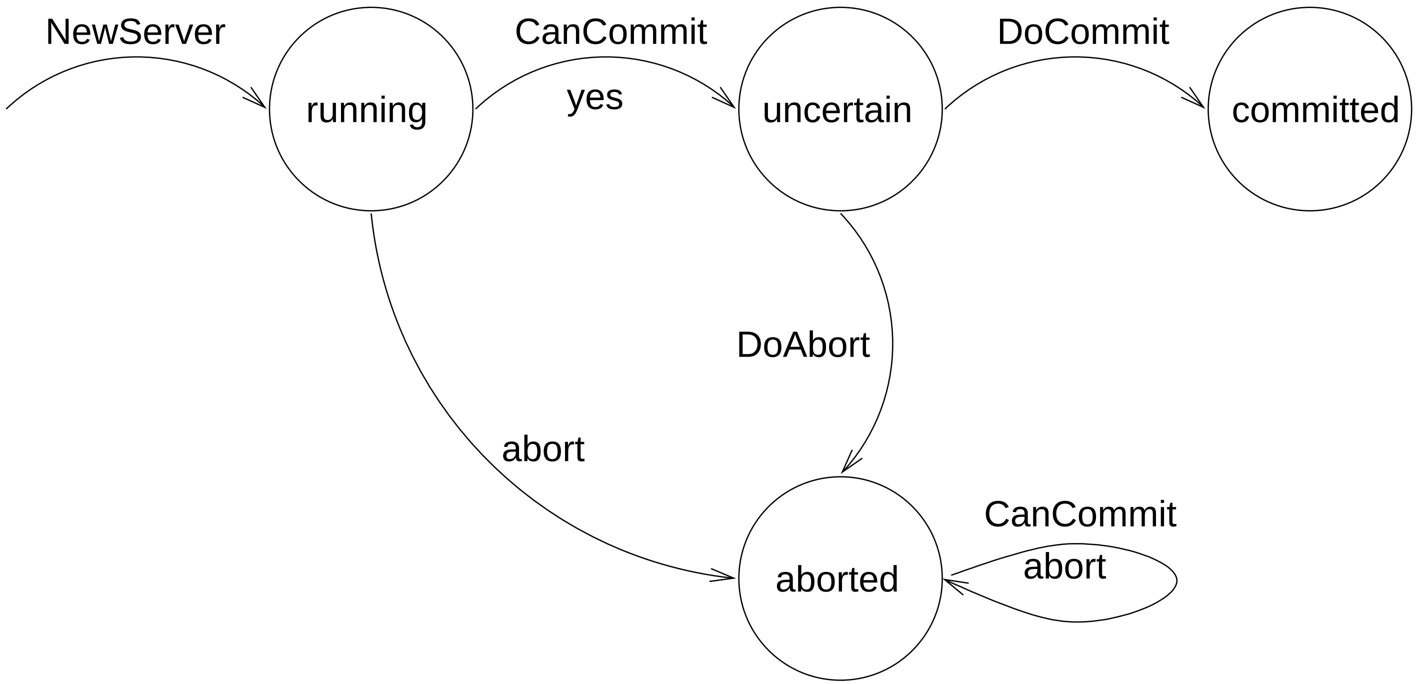
Basic protocol is called two-phase commit (2PC)

Two-phase commit: Coordinator:



1. sends `CanCommit`, receives `yes`, `abort`;
2. sends `DoCommit`, `DoAbort`

Two-phase commit: Worker:



1. receives `CanCommit`, sends `yes`, `abort`;
2. receives `DoCommit`, `DoAbort`

What are the assumptions?

Limitations:

- ➜ Once node voted “yes”, cannot change its mind, even if crashes.
  - Atomic state update to ensure “yes” vote is stable.
- ➜ If coordinator crashes, all workers may be blocked.
  - Can use different protocols (e.g. three-phase commit),
  - in some circumstances workers can obtain result from other workers.

Two-phase commit of nested transactions:

- ➜ Two-phase commit is required, as a worker might crash after provisional commit
- ➜ On `CanCommit` request, worker:
  - votes "no": if it has no recollection of subtransactions of committing transaction
    (i.e. must have crashed recently),
  - otherwise
    - aborts subtransactions of aborted transactions,
    - saves provisionally committed transactions in stable store,
    - votes "yes".

Two Approaches:

- ➜ Hierarchic 2PC
- ➜ Flat 2PC

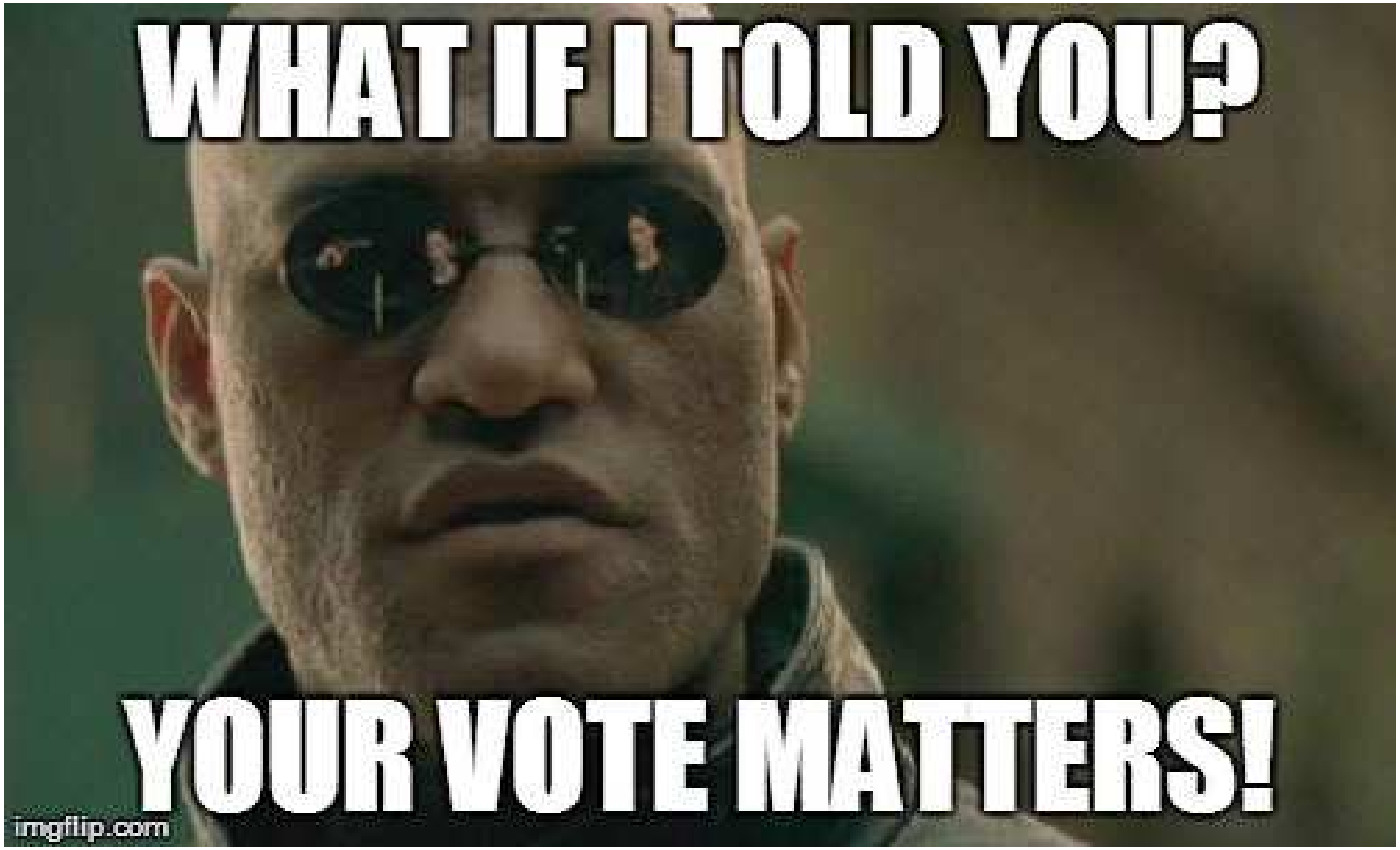
ELECTIONS

Coordinator:

- ➜ Some algorithms rely on a distinguished coordinator process
- ➜ Coordinator needs to be determined
- ➜ May also need to change coordinator at runtime

Election:

- ➜ Goal: when algorithm finished all processes agree who new coordinator is.


WHAT IF I TOLD YOU?
YOUR VOTE MATTERS!
imgflip.com

Determining a coordinator:

- ➜ Assume all nodes have unique id
- ➜ possible assumption: processes know all other process's ids but don't know if they are up or down
- ➜ Election: agree on which non-crashed process has largest id number

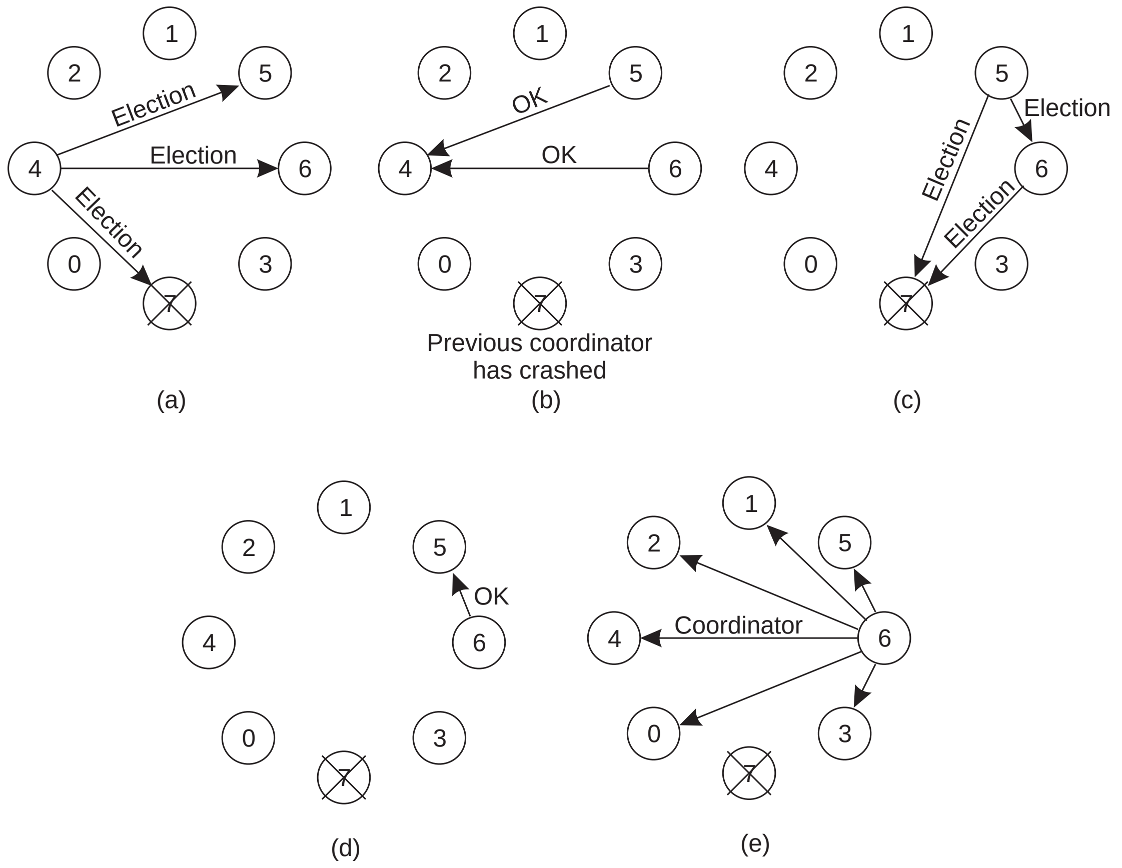
Requirements:

① **Safety:** A process either doesn't know the coordinator or it knows the id of the process with largest id number

② **Liveness:** Eventually, a process crashes or knows the coordinator

Bully algorithm

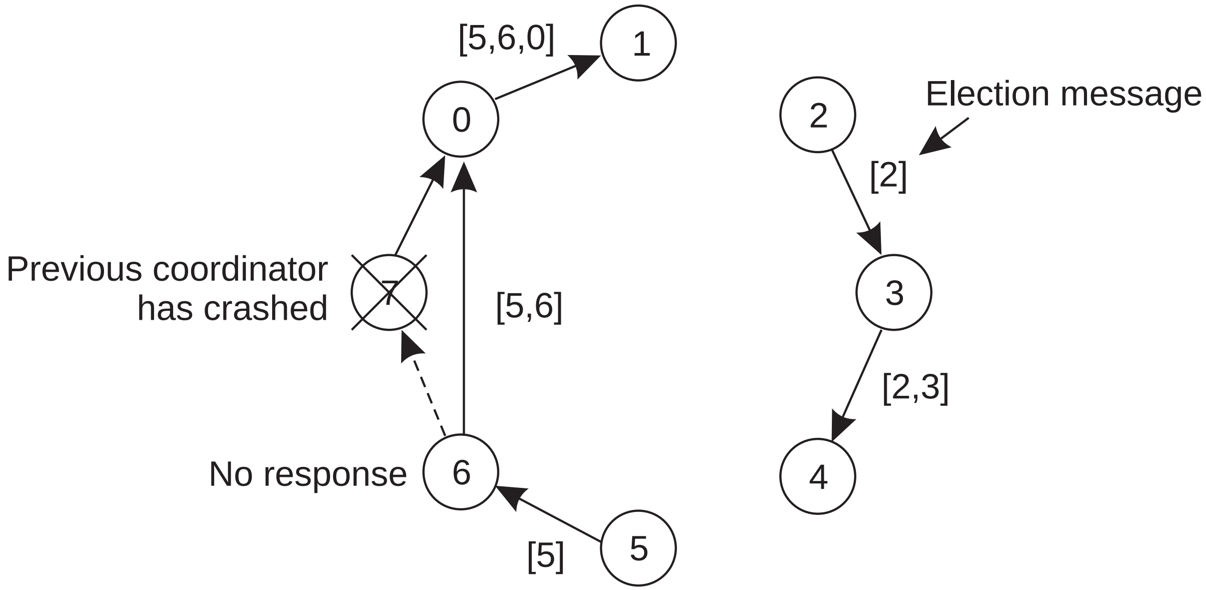
- Three types of messages:
  - *Election:* announce election
  - *Answer:* response to election
  - *Coordinator:* announce elected coordinator
- A process begins an election when it notices through a timeout that the coordinator has failed or receives an *Election* message
- When starting an election, send *Election* to all higher-numbered processes
- If no *Answer* is received, the election starting process is the coordinator and sends a *Coordinator* message to all other processes
- If an *Answer* arrives, it waits a predetermined period of time for a *Coordinator* message
- If a process knows it is the highest numbered one, it can immediately answer with *Coordinator*



What are the assumptions?

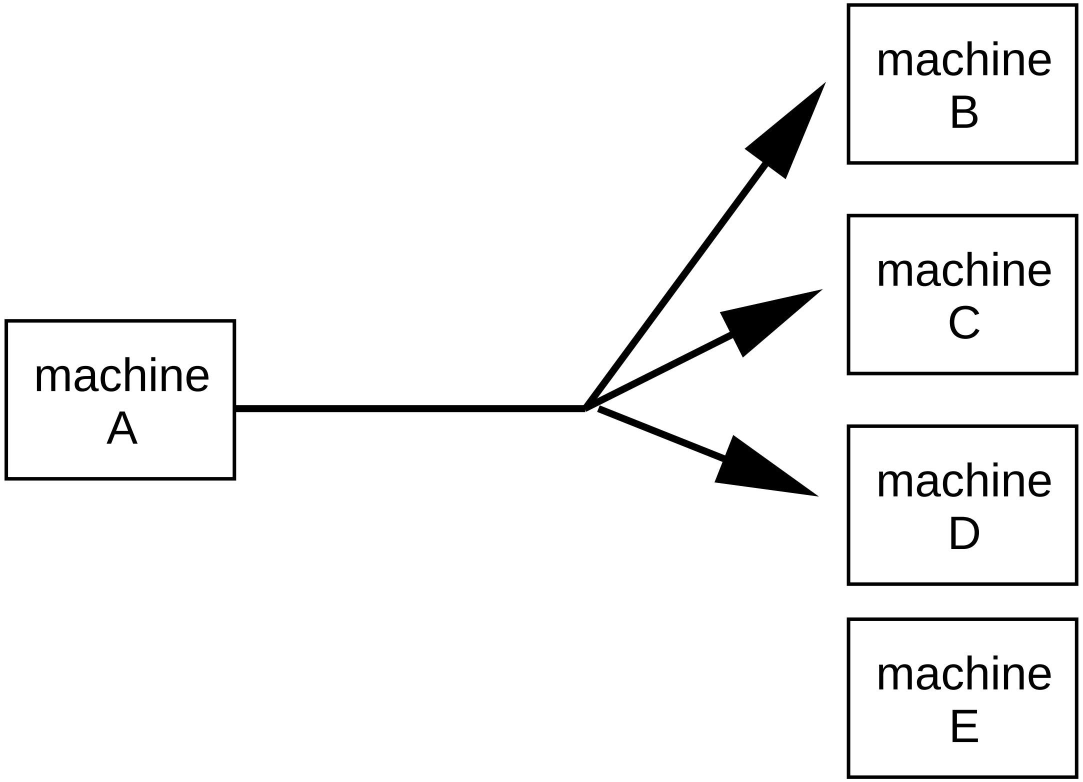
Ring Algorithm

- Two types of messages:
  - *Election:* forward election data
  - *Coordinator:* announce elected coordinator
- Processes ordered in ring
- A process begins an election when it notices through a timeout that the coordinator has failed.
- Sends message to first neighbour that is up
- Every node adds own id to *Election* message and forwards along the ring
- Election finished when originator receives *Election* message again
- Forwards message on as *Coordinator* message



What are the assumptions?

MULTICAST



- Sender performs a single `send()`
- Group of receivers
- Membership of group is transparent

Examples

Fault Tolerance:

- ➜ Replicated (redundant) servers
- ➜ Strong consistency: multicast operations

Service Discovery:

- ➜ Multicast request for service
- ➜ Reply from service provider

Performance:

- ➜ Replicated servers or data
- ➜ Weaker consistency: multicast operations or data

Event or Notification propagation:

- ➜ Group members are those interested in particular events
- ➜ Example: sensor data, stock updates, network status

PROPERTIES

Group membership:

- ➜ Static: membership does not change
- ➜ Dynamic: membership changes

Open vs Closed group:

- ➜ Closed group: only members can send
- ➜ Open group: anyone can send

Reliability:

- ➜ Communication failure vs process failure
- ➜ Guarantee of delivery:
  - ➜ all members (or none) – Atomic
  - ➜ all non-failed members

Ordering:

- ➜ Guarantee of ordered delivery
- ➜ FIFO, Causal, Total Order

Examples Revisited

Fault Tolerance:

- ➜ Reliability: Atomic
- ➜ Ordering: Total
- ➜ Membership: Static
- ➜ Group: Closed

Service Discovery:

- ➜ Reliability: No guarantee
- ➜ Ordering: None
- ➜ Membership: Static
- ➜ Group: Open

Performance:

- ➜ Reliability: Non-failed
- ➜ Ordering: FIFO, Causal
- ➜ Membership: Dynamic
- ➜ Group: Closed

Event or Notification propagation:

- ➜ Reliability: Non-failed
- ➜ Ordering: Causal
- ➜ Membership: Dynamic
- ➜ Group: Open

OTHER ISSUES

Performance:

- ➜ Bandwidth
- ➜ Delay

Efficiency:

- ➜ Avoid sending a message over a link multiple times (stress)
- ➜ Distribution tree
- ➜ Hardware support (e.g., Ethernet broadcast)

Network-level vs Application-level:

- ➜ Network routers understand multicast
- ➜ Applications (or middleware) send unicasts to group members
- ➜ Overlay distribution tree

Network-level Multicast

"You put packets in at one end, and the network conspires to deliver them to anyone who asks." Dave Clark

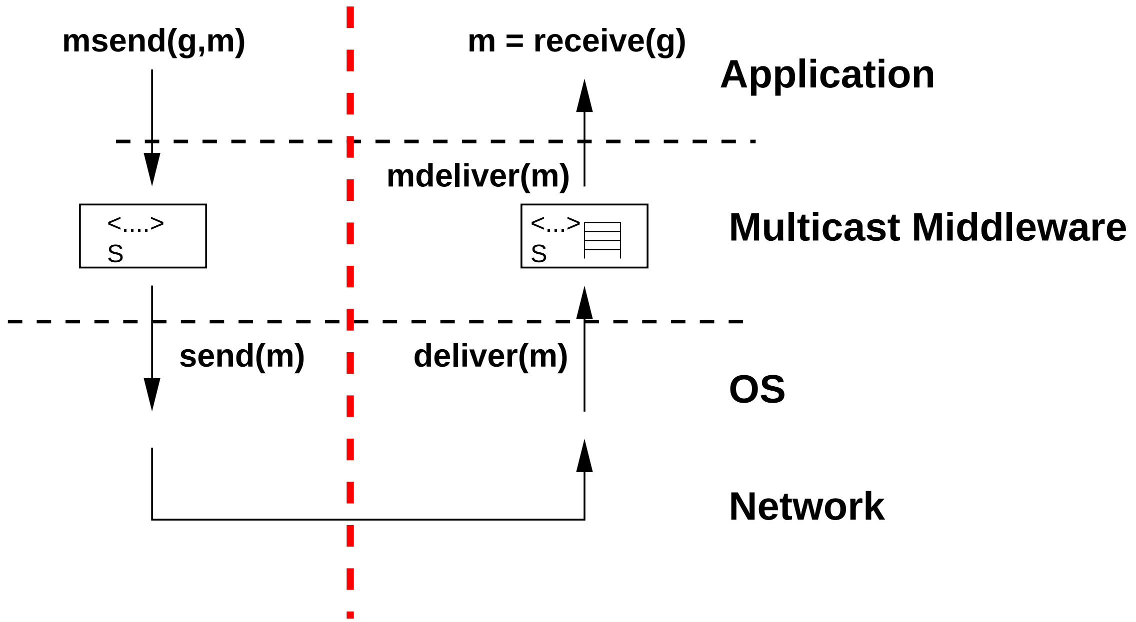
Ethernet Broadcast:

- ➜ all hosts on local network
- ➜ MAC address: FF:FF:FF:FF:FF:FF

IP Multicast:

- ➜ multicast group: class D Internet address:
- ➜ first 4 bits: 1110 (224.0.0.0 to 239.255.255.255)
- ➜ permanent groups: 224.0.0.1 - 224.0.0.255
- ➜ multicast routers
  - ➜ join group: Internet Group Management Protocol (IGMP)
  - ➜ set distribution trees: Protocol Independent Multicast (PIM)

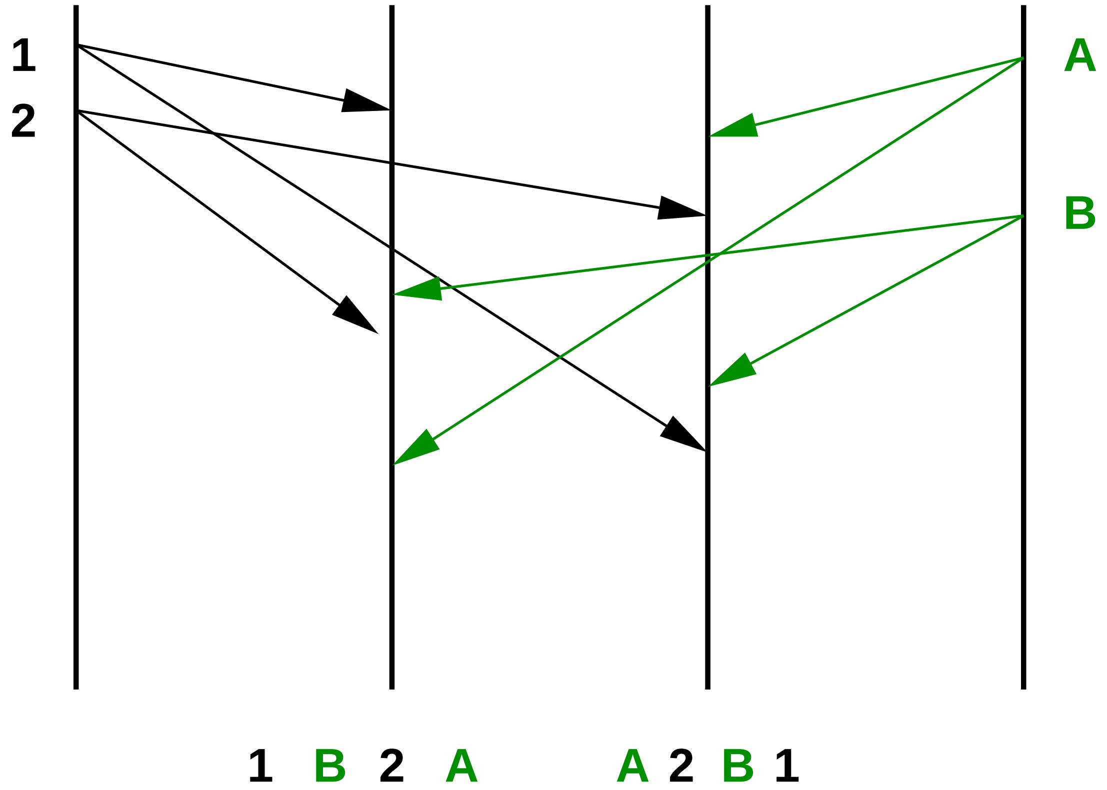
Application-level Multicast System Model



Assumptions:

- reliable one-to-one channels
- no failures
- single closed group

Basic Multicast

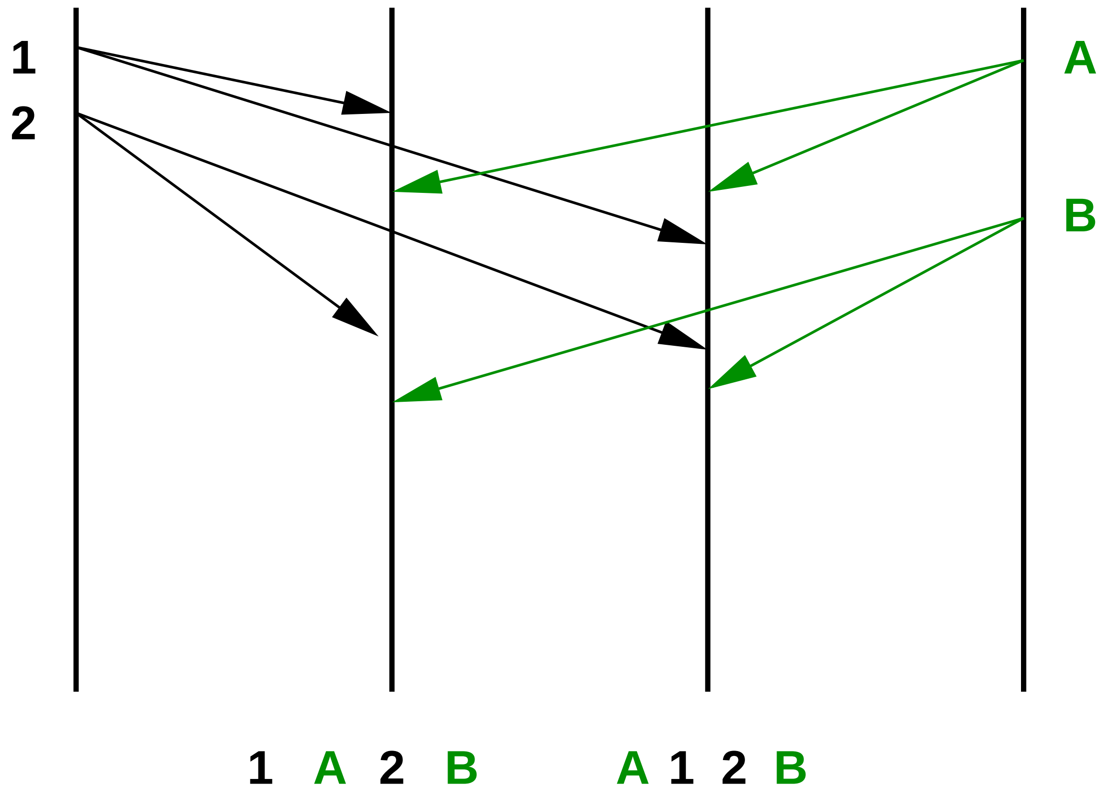


- ➜ no reliability guarantees
- ➜ no ordering guarantees

```
B-send(g,m) {
  foreach p in g {
   send(p, m);
  }
}

deliver(m) {
  B-deliver(m);
}
```

FIFO MULTICAST



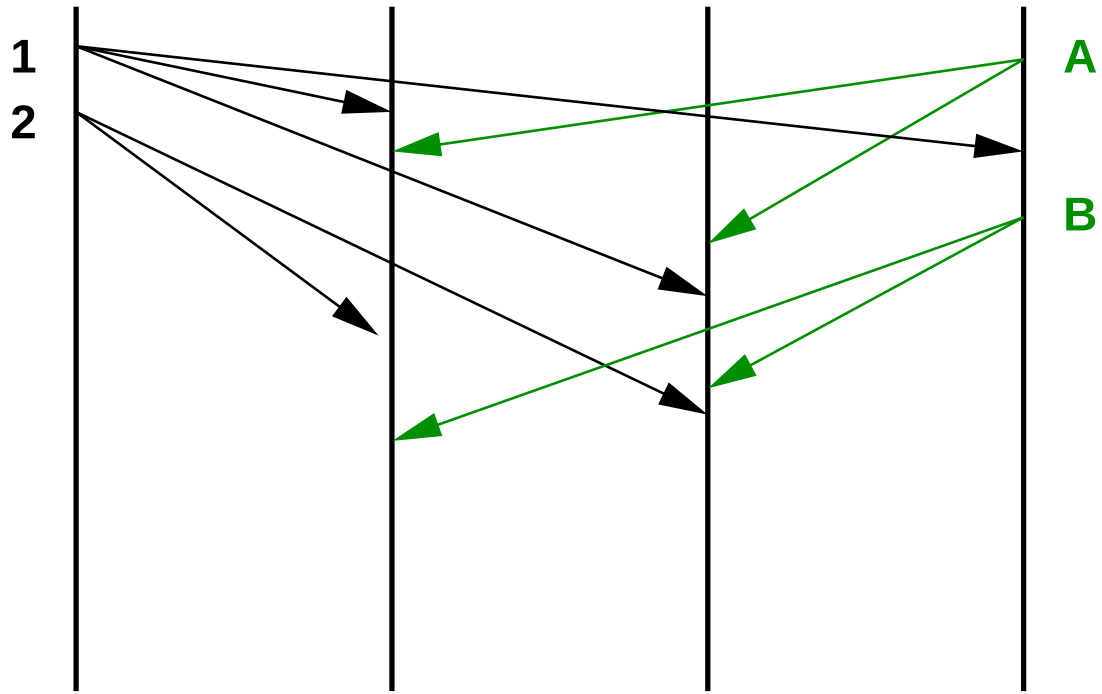
➜ order maintained per sender

```
FO-init() {
  S = 0;               // local sequence #
  for (i = 1 to N) V[i] = 0; // vector of last seen seq #s
}

FO-send(g, m) {
  S++;
  B-send(g, <m,S>);  // multicast to everyone
}
```

```
B-deliver(<m,S>) {
  if (S == V[sender(m)] + 1) {
    // expecting this msg, so deliver
    FO-deliver(m);
    V[sender(m)] = S;
  } else if (S > V[sender(m)] + 1) {
    // not expecting this msg, so put in queue for later
    enqueue(<m,S>);
  }
  // check if msgs in queue have become deliverable
  foreach <m,S> in queue {
    if (S == V[sender(m)] + 1) {
      FO-deliver(m);
      dequeue(<m,S>);
      V[sender(m)] = S;
} } }
```

CAUSAL MULTICAST



1 **A** **2** **B** **A** **1** **B** **2**

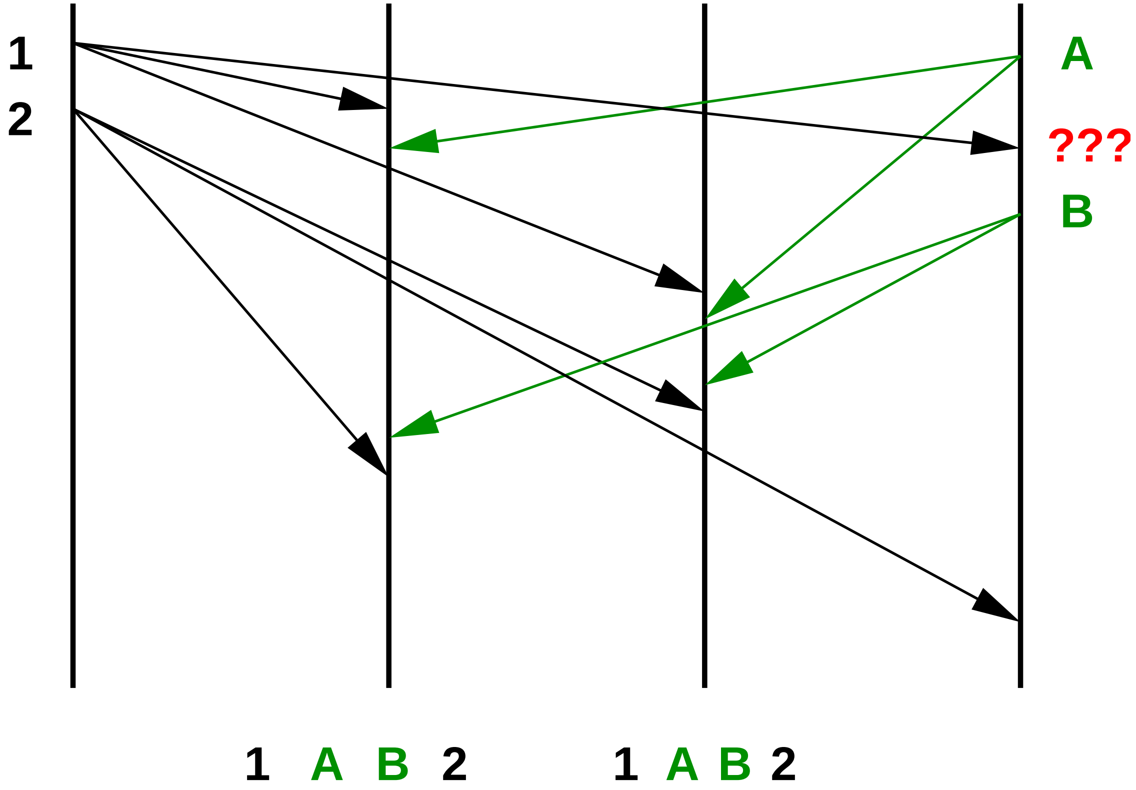
➜ order maintained between causally related sends

➜ 1 and A, 2 and B are concurrent

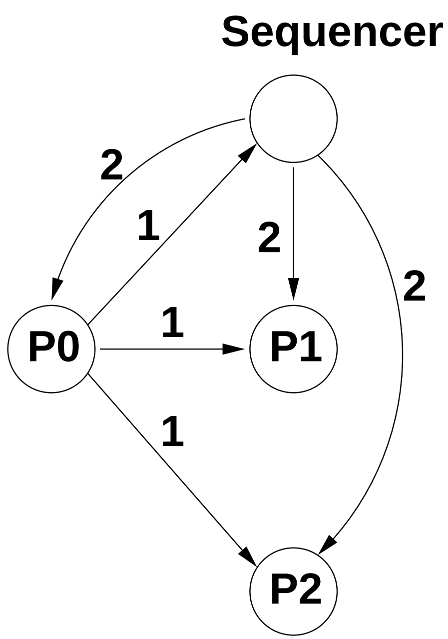
➜ 1 happens before B

```
CO-init() {
  // vector of what we've delivered already
  for (i = 1 to N) V[i] = 0;
}
CO-send(g, m) {
  V[i]++;
  B-send(g, <m,V>);
}
B-deliver(<m,Vj>) {  // j = sender(m)
  enqueue(<m,Vj>);
  // make sure we've delivered everything the message
  // could depend on
  wait until Vj[j] == V[j] + 1  and Vj[k] <= V[k] (k!= j)
  CO-deliver(m);
  dequeue(<m,Vj>);  V[j]++;
}
```

TOTALLY ORDERED MULTICAST

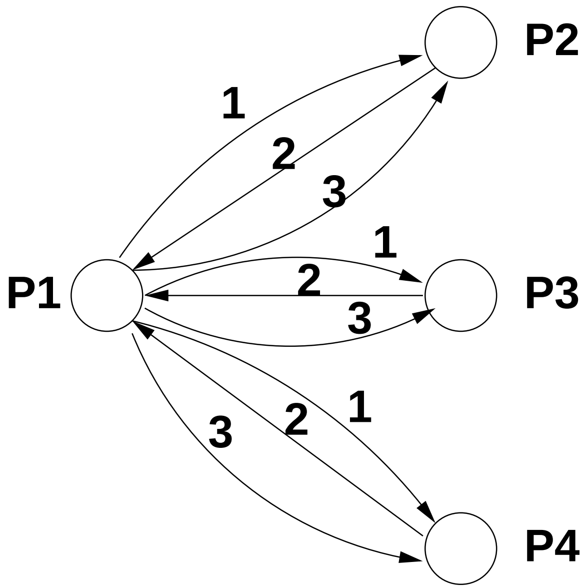


Sequencer Based:



1 – message
2 – sequence number

Agreement-based:



1 − message
2 − proposed sequence
3 − agreed sequence

Other possibilities:

- ➜ Moving sequencer
- ➜ Logical clock based
  - each receiver determines order independently
  - delivery based on sender timestamp ordering
  - how do you know you have most recent timestamp?
- ➜ Token based
- ➜ Physical clock ordering

Hybrid Ordering:

- ➜ FIFO + Total
- ➜ Causal + Total

Dealing with Failure:

- ➜ Communication
- ➜ Process

HOMEWORK

➜ We only discussed distributed transactions, but not replicated transactions. What changes if we introduce replication? Do the techniques we've discussed still work?

➜ How well does 2PC deal with failure? Can you improve it to deal with more types of failure?

Hacker's edition:

➜ Do the Multicast (Erlang) exercise

Reading List

Optional

Total Order Broadcast and Multicast Algorithms: Taxonomy and Survey everything you always wanted to know...

Elections in a distributed computing system Bully algortihm