Distributed Computing III

Murphy was an optimist.

— *O'Toole's Commentary*

CSSE6400

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April 22, 2024

Question

What communication faults may occur?

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What communication faults may occur?

Answer

- Message not delivered

Lost in transit.

Question

What communication faults may occur?

Answer

- Message not delivered
- Message delayed

Network delay or receiver overloaded, but message will be processed later.

Question

What communication faults may occur?

Answer

- Message not delivered
- Message delayed
- Receiver failed

Receiver software has crashed or node has died.

Question

What communication faults may occur?

Answer

- Message not delivered
- Message delayed
- Receiver failed
- Receiver busy

Receiver temporarily not replying
(e.g. garbage collection has frozen other processes).

Question

What communication faults may occur?

Answer

- Message not delivered
- Message delayed
- Receiver failed
- Receiver busy
- Reply not received

Request was processed but reply lost in transit.

Question

What communication faults may occur?

Answer

- Message not delivered
- Message delayed
- Receiver failed
- Receiver busy
- Reply not received
- Reply delayed

Reply will be received later.

Question

How do we detect faults?

Question

How do we detect faults?

Answer

- No listener on port – RST or FIN packet

Assumes node is running & reachable.
OS should close or refuse connection.
Error packet may be lost in transit.

Question

How do we detect faults?

Answer

- No listener on port – RST or FIN packet
- Process crashes – Monitor report failure

Assumes node is running & reachable.
Most reliable.

Question

How do we detect faults?

Answer

- No listener on port – RST or FIN packet
- Process crashes – Monitor report failure
- IP address not reachable – unreachable packet

Router has to determine address is not reachable, which is no easier than for your application.

Question

How do we detect faults?

Answer

- No listener on port – RST or FIN packet
- Process crashes – Monitor report failure
- IP address not reachable – unreachable packet
- Query switches

Need permissions to do this.
Will only have this in your own data centre.

Question

How do we detect faults?

Answer

- No listener on port – RST or FIN packet
- Process crashes – Monitor report failure
- IP address not reachable – unreachable packet
- Query switches
- Timeout

UDP reduces network transmission time guarantee – does not perform retransmission.

Question

What to do if fault is detected?

Question

What to do if fault is detected?

Answer

- Retry
- Restart

- How many retries? How often?
- Exponential backoff with jitter
- How long to wait to restart?
- Too long reduces responsiveness.
- Unacknowledged messages need to be sent to other nodes – reducing performance.
- Too short may prematurely declare nodes dead.
- May lead to contention – two nodes processing the same request.
- May lead to cascading failure – load is sent to other nodes, slowing them down so they are then declared dead . . . .

Definition 1. Idempotency

Repeating an operation does not change receiver's state.

- Idempotent consumer pattern
- Tag messages with an ID, so repeated messages can be ignored
- Or, redo messages that do not change state (e.g. queries)

Byzantine Generals Problem

- n generals need to agree on plan
- Can only communicate via messenger
- Messenger may be delayed or lost
- Some generals are traitors
  - Send dishonest messages
  - Pretend to have not received message
  - Send messages pretending to be another general

Link analogy to Byzantine faults

Definition 2. Byzantine Faults

Nodes in a distributed system may 'lie'.
— Send faulty or corrupted messages or responses.

- A message that causes the receiver to fail.
- Incorrect responses (e.g. they have finished processing a message but haven't).
- Can be due to faults or malicious hosts.
- Difficult to deal with all possible variations of these faults.

Question

Can we design a system to be Byzantine fault tolerant?

Question

Can we design a system to be Byzantine fault tolerant?

Answer

Yes, but, it is *challenging*.

- Most systems don't attempt to
- Some need to (e.g. safety critical systems, blockchain, ...)
- Refer to CSSE3012 Safety Critical guest lecture.

Limited Fault Tolerance

- Validate format of received messages
  - Need strategy to handle & report errors

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- Santise inputs
  - Assume any input from external sources may be malicious

Limited Fault Tolerance

- Validate format of received messages
  - Need strategy to handle & report errors
- Santise inputs
  - Assume any input from external sources may be malicious
- Retrieve data from multiple sources
  - If possible
  - e.g. Multiple NTP servers

Assumption

If all nodes are part of our system, we may assume there are no Byzantine faults.

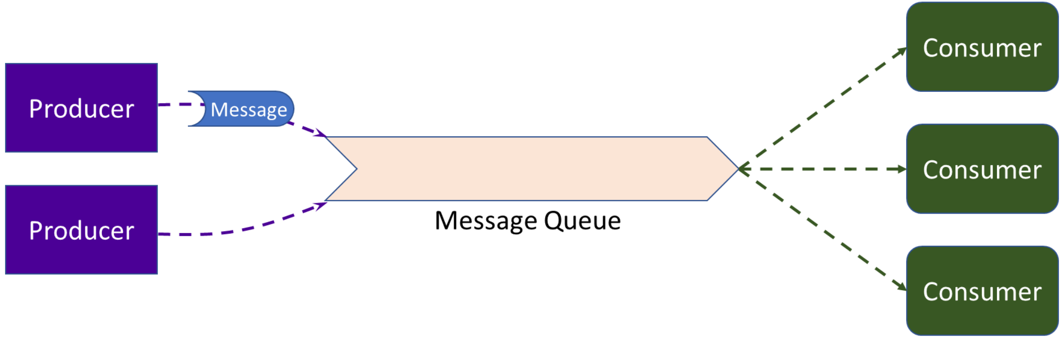
- Santise user input
- Byzantine faults may still arise
  - Logic defects
    - Same code is usually deployed to all replicated nodes, defeating easy fault tolerance solutions

Definition 3. Poison Message

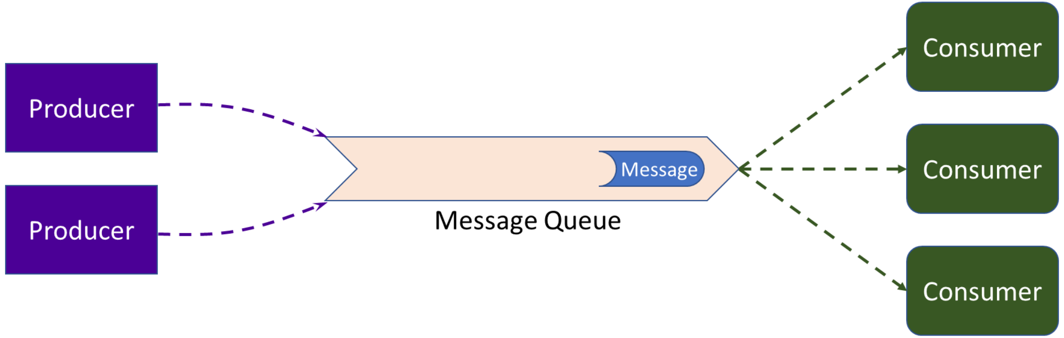
A message that causes the receiver to fail.

- Could literally cause the receiver to crash
- Often the receiver just cannot process the message and aborts processing

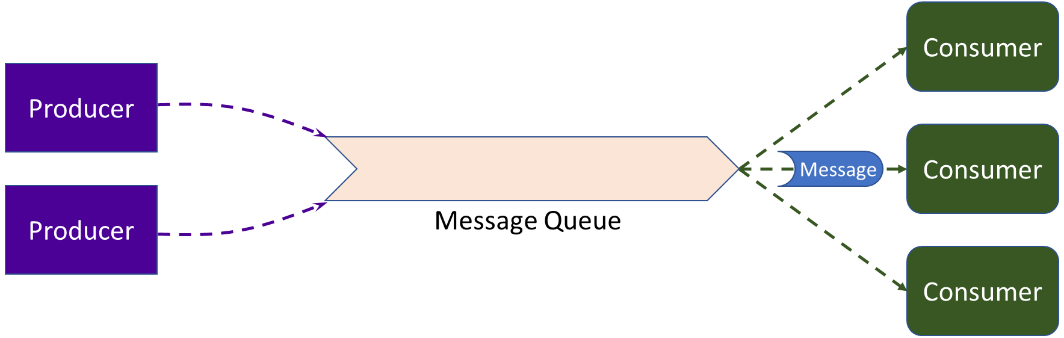
Normal Message Flow



- Normal message/event is sent from a Producer.



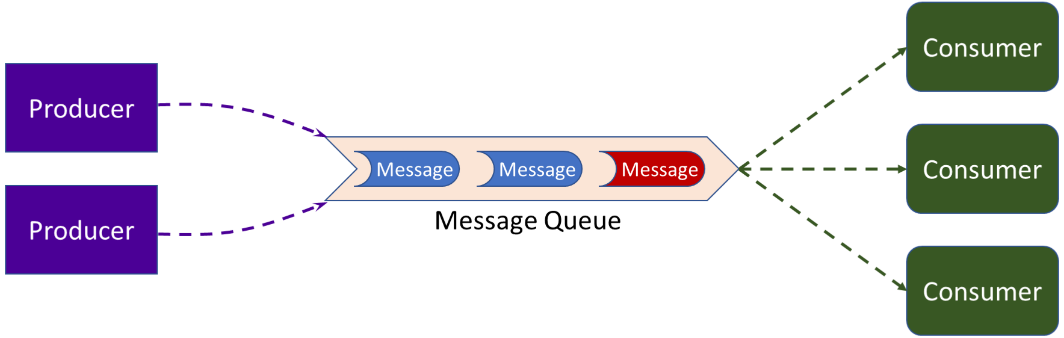
- Normal message/event is queued (in Message Queue).



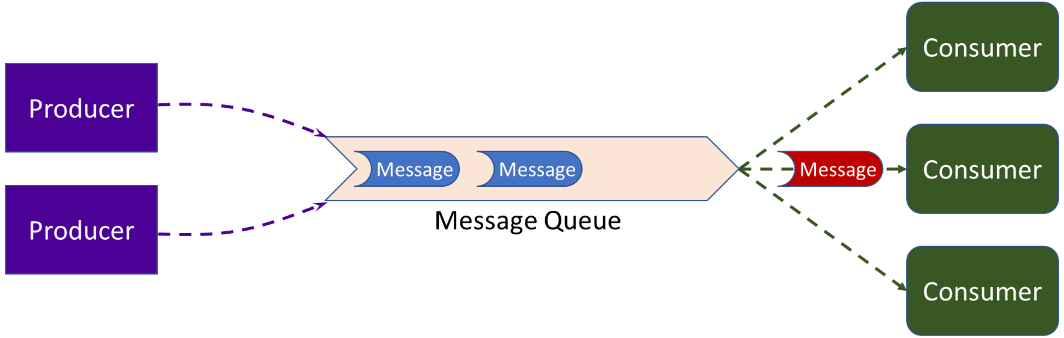
- Normal message/event is dequeued and processed by a Consumer.

Poison Message

- Receiver can't process message.
- Always fails – Not due to transient failure.
- Failed messages are retried.
- Returned to front of queue – Preserve message order.
- Next receiver fails to process message – Infinite loop.
- Blocks sending of following messages.



- This set of slides is an example of a poison message blocking the queue.
- Poison message is at head of queue. blocking issue.



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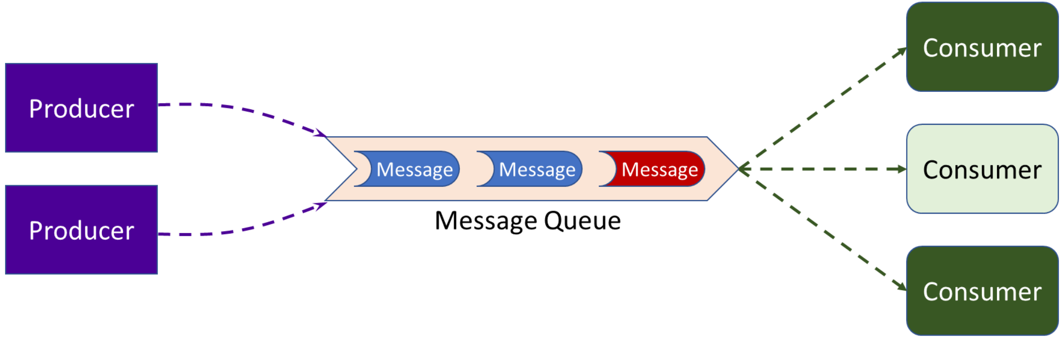
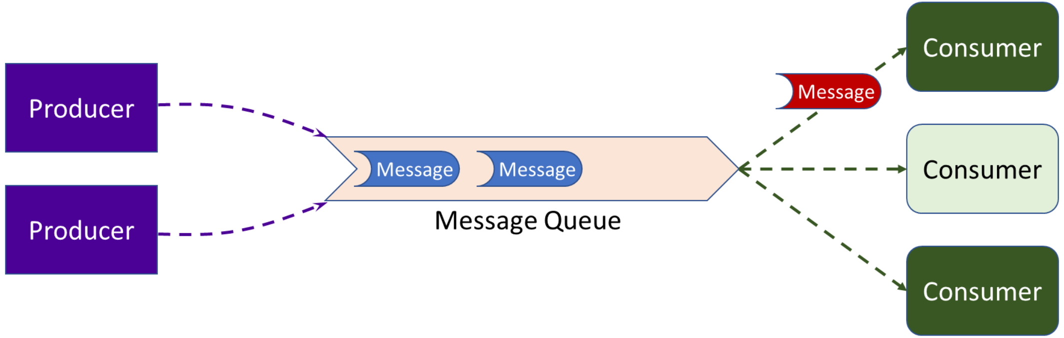
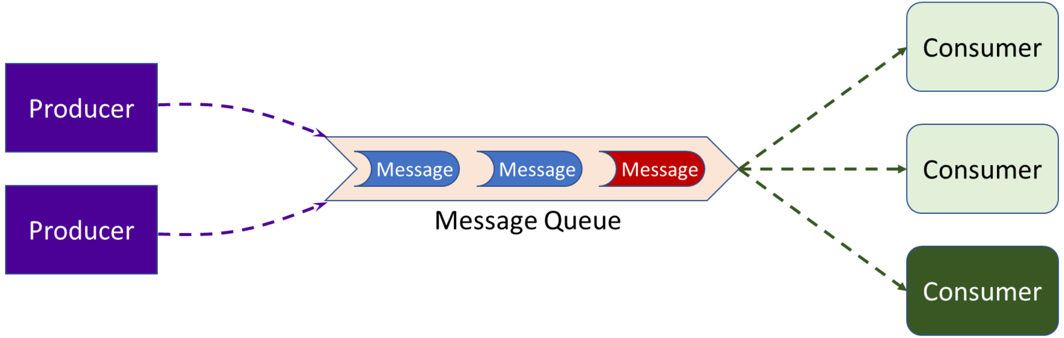
- Poison message is dequeued by a Consumer.



- This set of slides is an example of a poison message blocking the queue.
- Consumer fails (crashes).
- Poison message is added back to the head of the queue (re-try).



- This set of slides is an example of a poison message blocking the queue.
- Next Consumer dequeues poison message and fails (crashes).



- This set of slides is an example of a poison message blocking the queue.
- Poison message is added back to the head of the queue again (re-try).
- Infinite loop ...
- **Comment** that poison messages block processing regardless of how they're delivered.
- A message queue or service isn't the key blocking point.
- Async messages sent directly to a consumer requires it to queue them as they're processed, leading to the same blocking issue.

Question

What causes a message to be poisonous?

Question

What causes a message to be poisonous?

Answer

- Content is invalid
  - e.g. Invalid product id sent to purchasing service
  - Error handling doesn't cater for error case

Invalid content may be

- corrupted data,
- old version of data structure,
- incorrect data, or
- malicious data.

Question

What causes a message to be poisonous?

Answer

- Content is invalid
  - e.g. Invalid product id sent to purchasing service
  - Error handling doesn't cater for error case
- System state is invalid
  - e.g. Add item to shopping cart that has been deleted
  - Logic doesn't handle out of order messages
    - Insidious asynchronous faults

Invalid state may be

- events out of order (e.g. delete then update),
- logic error making state invalid, or
- external corruption of persistent state.

Detecting Poison Messages

Retry counter – with limit

- Where is counter stored?
  - Memory – What if server restarts?
  - DB – Slow
  - Must ensure counter is reset, regardless of how message is handled
    - e.g. Message is manually deleted

Detecting Poison Messages

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Message service may have a timeout property

- Message removed from queue
  - Pending messages get older while waiting for poison message
  - Transient network faults may exceed timeout

Monitoring service

- Trigger action if message stays at top of queue for too long
- Can check for queue errors
  - No messages are being processed
  - Restart message service

Discard message

- System must not require guarantee of message delivery
- Suitable when message processing speed is most important

Handling Poison Messages

Discard message

- System must not require guarantee of message delivery
- Suitable when message processing speed is most important

Always retry

- Requires mechanism to fix message
  - Often requires manual intervention
- Suitable when message delivery is most important
- Very long delays in processing

Handling Poison Messages

Dead-letter queue

- Long transient failures result in adding many messages
  - e.g. Network failure
- Requires manual monitoring and intervention
- System must not require strict ordering of messages
- Suitable when message processing speed is important

Handling Poison Messages

Retry queue

- Transient failures also added
- Use a previous strategy to deal with poison messages
- System must not require strict ordering of messages
- Suitable when message processing speed is very important
  - Main queue is never blocked
  - Receivers need to process from two message queues

Definition 4. Poison Pill Message

Special message used to notify receiver it should no longer wait for messages.

Emphasise that this is **different** to a poison message

Question

Why use a poison pill message?

Question

Why use a poison pill message?

Answer

Graceful shutdown of system.

- Implementation is challenging with multiple producers and/or consumers.
- It must be the last message received by *all* consumers.

Question

How to order asynchronous messages?

Question

How to order asynchronous messages?

Answer

- Timestamps?
  - Can't keep clocks in sync
  - Limited clock precision

- Trying to sync with NTP is unreliable
- Network delays during sync
- Clock drift between syncs
- Finite precision – two events may end up with the same timestamp, if they occur in quick succession

§ *Data Issues*

Eventual Consistency weak guarantee

Linearisability strong guarantee

Causal Ordering strong guarantee

Eventual Consistency

- Allows stale reads
- May be appropriate for some systems
  - e.g. Social media updates[1]

[1] See Distributed II slides 41 - 46.

- Once value is written, all reads see same value
  - Regardless of replica read from

Abstraction over replicated database.
Used when uniqueness needs to be guaranteed.

- Once value is written, all reads see same value
  - Regardless of replica read from
- Single-leader replication
  - Read from leader
  - Read from synchronous follower

SLR – defeats most performance benefits.
Maintains reliability benefits.

- Once value is written, all reads see same value
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- Multi-leader replication can't be linearised

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- Multi-leader replication can't be linearised
- Leaderless replication
  - Lock value on quorum *before* writing

Leaderless – similar performance cost to SLR.

Causal Order

- Order is based on causality
  - What event needs to happen before another
  - Allows concurrent events

- Linearisation defines a *total* order.
- Causal ordering defines a *partial* order.
- e.g. Git repo history with branching as *causal order*.
- Not as strict as linearisability, so less performance cost.

- Order is based on causality
  - What event needs to happen before another
  - Allows concurrent events
- Single-leader replication
  - Record sequence number of writes in log
  - Followers read log to execute writes

Causal Order

- Order is based on causality
  - What event needs to happen before another
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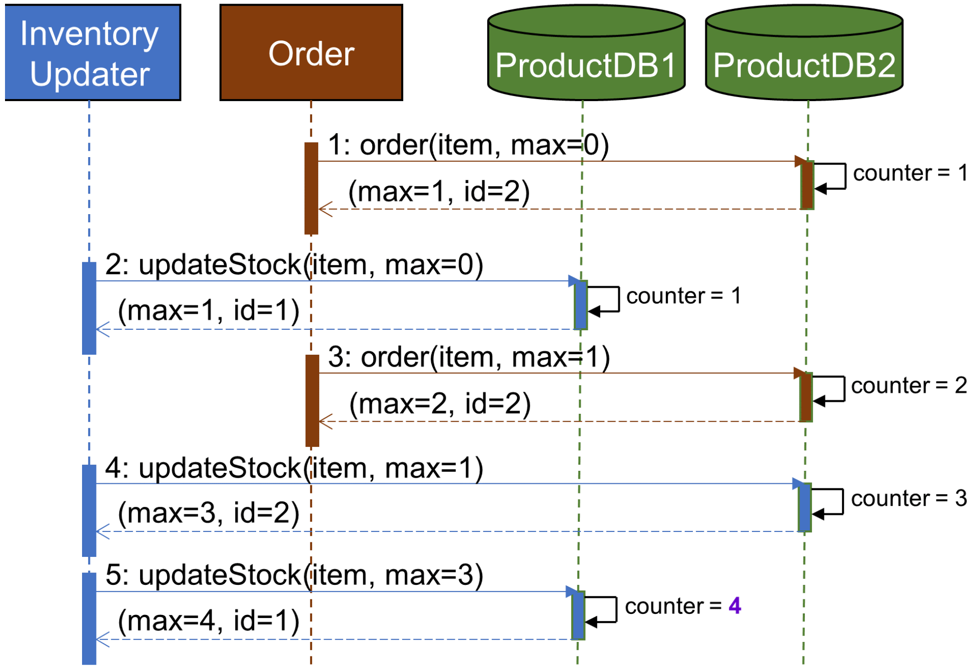
- Single-leader replication
  - Record sequence number of writes in log
  - Followers read log to execute writes
- Lamport timestamps

Next slide is an example of Lamport timestamps.



- Each node has an id, & counts number of operations.
- Timestamp is a tuple $(counterValue, nodeID)$.
- $nodeID$ guarantees every timestamp is unique, even if they have the same counter value.
- Every node stores the maximum counter value seen so far.
- Maximum is passed in every request to another node.
- If a node receives a request or response with a maximum counter value greater than its own counter value, it increases its own counter to the new maximum.
- **Message 4:** InventoryUpdater sends its current maximum value (**1**). ProductDB2's counter is **2**, so it increases it to **3** & returns to InventoryUpdater. InventoryUpdater records **3** as its new maximum value. **Message 5:** Updates ProductDB1's max value & then counts operation.

Definition 5. Consensus

A set of nodes in the system agree on some aspect of the system's state.

- Abstraction to make it easier to reason about system state.
- e.g. Selecting Leader DB if leader fails, or some Followers think it has failed.

Uniform Agreement All nodes must agree on the decision

Integrity Nodes can only vote once

Validity Result must have been proposed by a node

Termination Every node that doesn't crash must decide

- *Uniform Agreement* and *Integrity* are key
- *Validity* avoids nonsensical solutions
  - e.g. Always agreeing to a null decision
- *Termination* enforces fault tolerance
  - Requires making progress towards a solution

Definition 6. Atomic Commit

All nodes participating in a distributed transaction need to form consensus to complete the transaction.

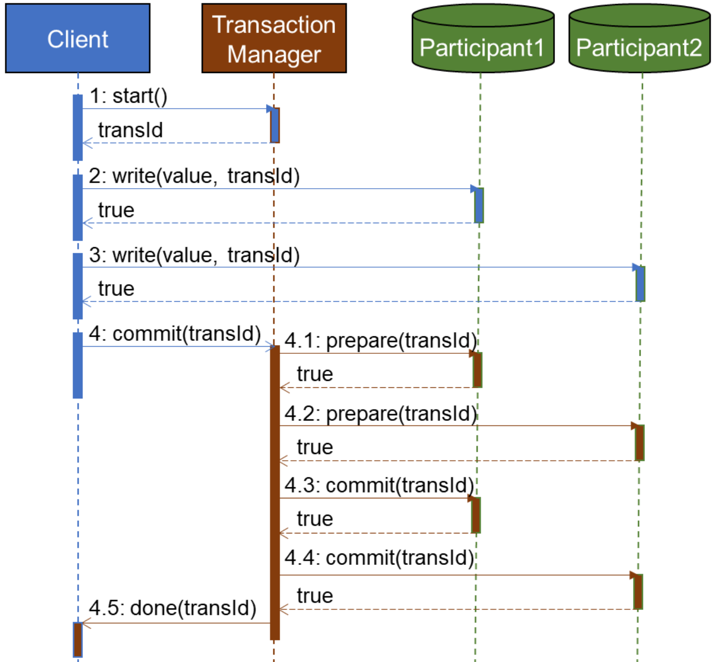
Based on transaction atomicity from ACID (Atomicity, Consistency, Isolation, Durability)

Prepare Confirm nodes can commit transaction

Commit Finalise commit once consensus is reached

- Abort if consensus can't be reached

Two-Phase commit example is on next slide.



- Transaction ID used to track writes
- Prepare does all steps of a commit, *aside* from confirming it
  - It cannot be revoked by participant
- Commit intent is recorded in log before sending to participants
- Even if a participant fails, commit can proceed when it recovers
- Comment on *performance costs*

Distributed Systems Timing Assumptions

- Synchronous System
  - Not realistic due to faults above
  - Minimal performance benefit

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- Partially Synchronous System
  - Assumes important message order is preserved
  - Assumes most faults are rare & transient
  - Error handling to catch faults

Distributed Systems Timing Assumptions

- Synchronous System
  - Not realistic due to faults above
  - Minimal performance benefit
- Partially Synchronous System
  - Assumes important message order is preserved
  - Assumes most faults are rare & transient
  - Error handling to catch faults
- Asynchronous System
  - No timing assumptions
  - Important message order managed by application
  - Difficult & limited design

Distributed Systems Node Failure Assumptions

- Crash Stop
  - Node fails and never restarts

Cloud-based system that kills crashed nodes.

Distributed Systems Node Failure Assumptions

- Crash Stop
  - Node fails and never restarts
- Crash Recovery
  - Node fails and restarts
    - Requires persistent memory for recovery close to prior state

- Any system that allows nodes to be restarted.
- May lose some steps in memory for *non-critical* tasks.

Distributed Systems Node Failure Assumptions

- Crash Stop
  - Node fails and never restarts
- Crash Recovery
  - Node fails and restarts
    - Requires persistent memory for recovery close to prior state
- Arbitrary Failure
  - Nodes may perform spurious or malicious actions
    - Byzantine faults

Nodes may send faulty, corrupt or malicious messages.

- Distributed systems are hard to build
- Large systems have to be distributed
  - Monoliths can't scale to millions of users
- Use environments, tools & libraries
  - Leaverage others' experience
- CSSE7610 Concurrency: Theory & Practice
  - Prove correctness of concurrent & distributed systems