Reliability: Replication
Topics in Distributed Coordination and Distributed Transactions

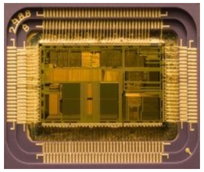
ACS, Yongluan Zhou

Do-it-yourself recap: Replication

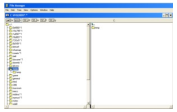
- **MAKE COPIES!! ☺**
  - State-machine replication
  - Asynchronous replication
    - Primary-Site
    - Peer-to-Peer
  - Synchronous replication
    - Read-Any, Write-All
    - Quorums

Replicated Interpreter

(loop (print (eval (read))))



Replicated Memory



- Techniques only good enough for a specific **failure model**
  - **Byzantine vs. crash vs. fail-stop**
  - What was the difference between synchronous and asynchronous replication?
  - What is the difference between the failure models above?

What should we learn today?

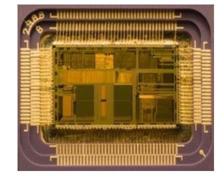
- Explain the difficulties of **guaranteeing atomicity in a replicated distributed system**
- Explain the **notion of state-machine replication** and the ISIS algorithm to **totally ordered multicast** among replicas
- Describe the implications of the **FLP impossibility result** and possible workarounds
- Explain mechanisms necessary for **distributed transactions**, such as distributed locking and distributed recovery
- Explain the operation of the **two-phase commit protocol** (**2PC**)
- Predict outcomes of 2PC under failure scenarios

Replication

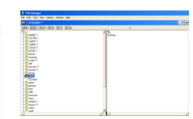
- **MAKE COPIES!!** ☺
  - State-machine replication
  - Asynchronous replication
    - Peer-to-Peer
    - Primary-Site
  - Synchronous replication
    - Read-Any, Write-All
    - Quorums

(loop (print (eval (read))))

Replicated Interpreter



Replicated memory



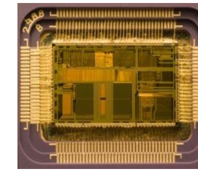
- Techniques only good enough for a specific **failure model**
  - Nuclear bomb
  - Component maliciously outputs random gibberish (**Byzantine**)
  - Components **crash** without telling you anything
  - Components are **fail-stop**

State Machines

- A state machine consists of
  - State variables
    - encoding its state
  - Instructions
    - transforming its state

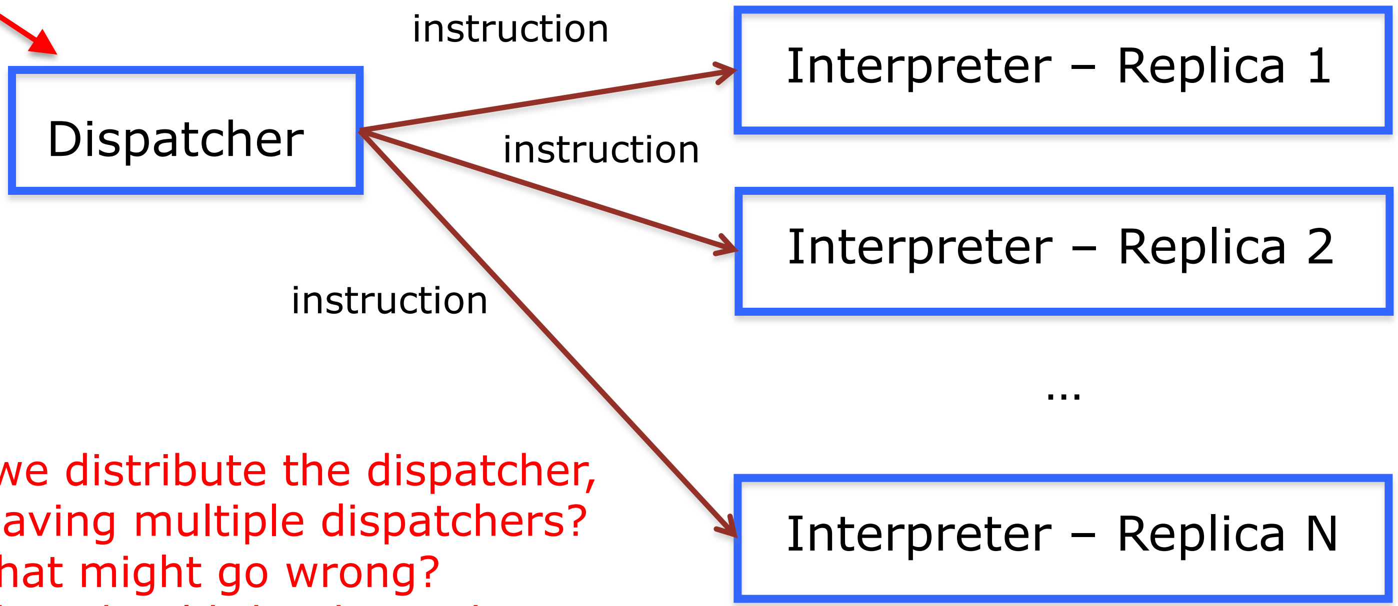
State-Machine Replication (or Active Replication)

(loop (print (eval (read))))



- Assumption
  - Instructions of interpreter are deterministic!
  - If replicas of interpreter get same inputs, they will go to the same state and produce the same output

Single point of failure?

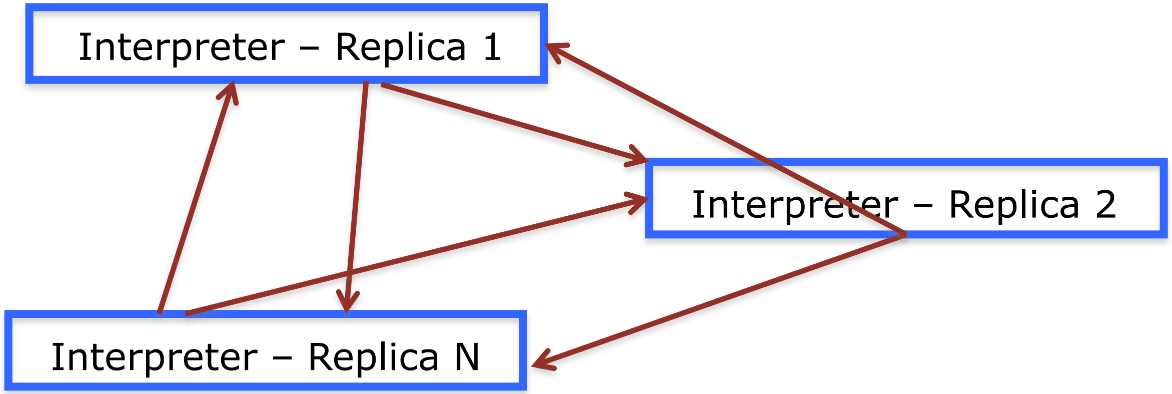


Can we distribute the dispatcher, i.e. having multiple dispatchers?

- What might go wrong?
- What should the dispatchers ensure when sending the instructions to the replicas?

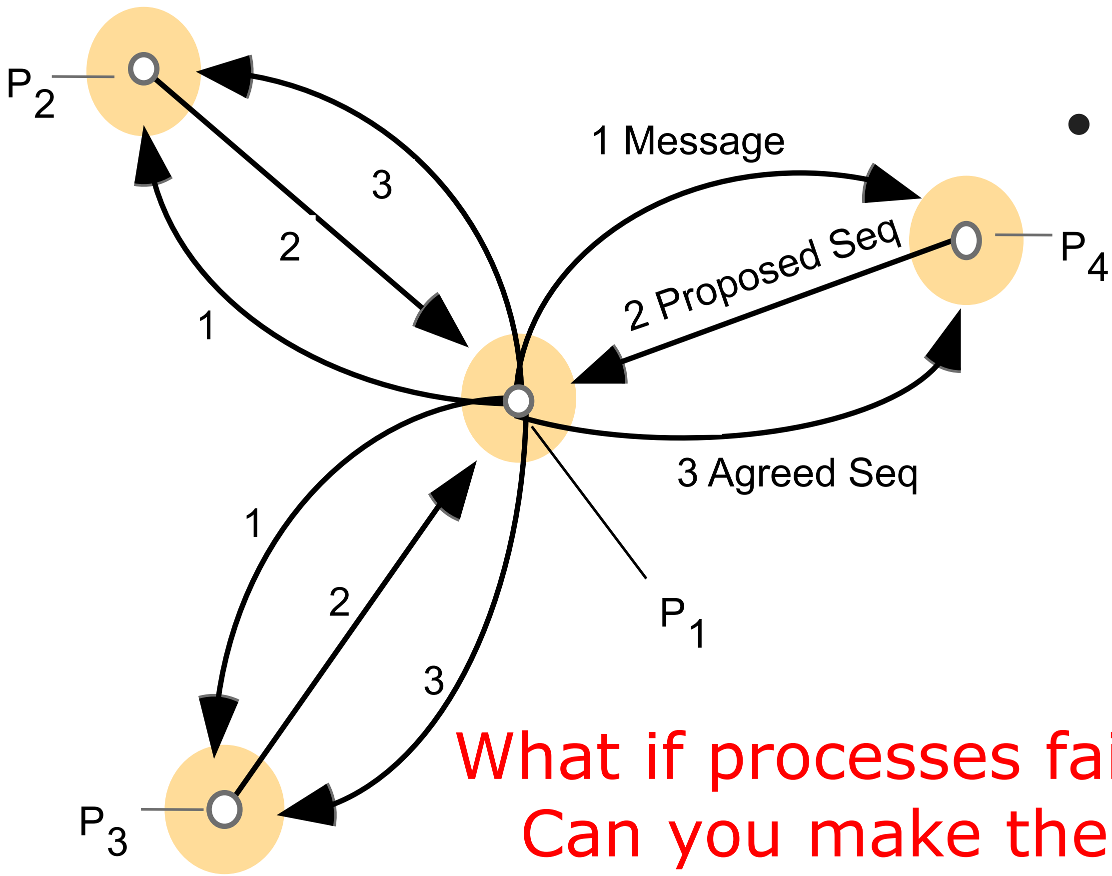
Multicast: Distributing the Dispatcher

- Replicas implement **multicast** operation → internalize dispatcher



- Must ensure **atomic** operation execution on all replicas
  - **All-or-nothing:** either in all correct replicas or none
    - Also called **Agreement**
  - **Before-or-after:** Equivalent to a total order
    - Also called **Order**
  - With at most *f* failures:
    - ***Fail-stop:*** requires *at least* N = *f* + 1 replicas
    - ***Byzantine:*** requires *at least* N = 2*f* + 1 replicas

Totally Ordered Multicast (ISIS)



- Assume for now no failures
- **Idea**
  - Process 1 sends message with identifier i to group
  - Every process p replies with proposed *seq#* = $max(accepted_p, proposed_p) + 1$
  - Process 1 selects maximum number and sends it to group
    - Note: ties in numbering broken by process numbers

What if processes fail?
Can you make the multicast reliable?

Source: Coulouris et al (partial)

Reliable and Totally Ordered Multicast?

- If network **asynchronous** and assuming **crash** failures, **guaranteeing** reliable **and** totally ordered multicast is **IMPOSSIBLE**

- Fischer, Lynch, Patterson (FLP) result → Impossibility of Consensus
  - Set of processes with single binary variable
  - Want to decide outcome as 0 or 1 by just exchanging messages
  - **Intuition:** cannot make the difference between crashed process and process running very slowly
  - Adversary can **delay** consensus indefinitely
  - Does not mean that consensus cannot be reached in some cases!

Where to go from here?

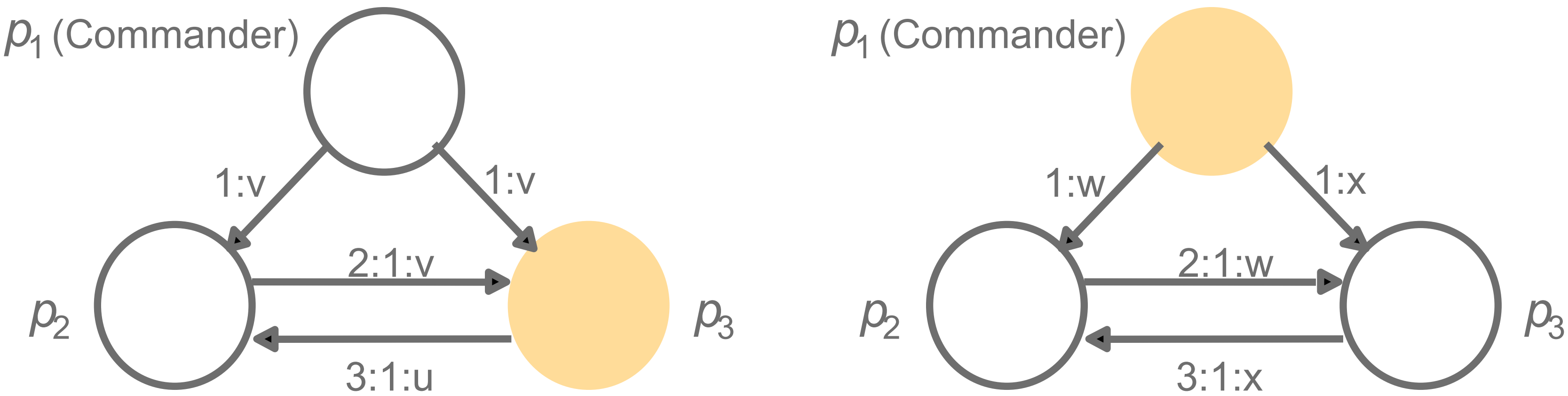
- If network **asynchronous** and assuming **crash** failures, **guaranteeing** reliable **and** totally ordered multicast is **IMPOSSIBLE**

- **Solution 1:** Make model **fail-stop**, not crash
  - Instead of asynchronous system, make system behave as a (partially) synchronous one with reliable failure detector, e.g., timeout
  - Use failure detector to flag failed processes, no doubts
- **Solution 2:** Design **protocol that guarantees safety**, even if it cannot guarantee progress
  - Paxos example of such a protocol

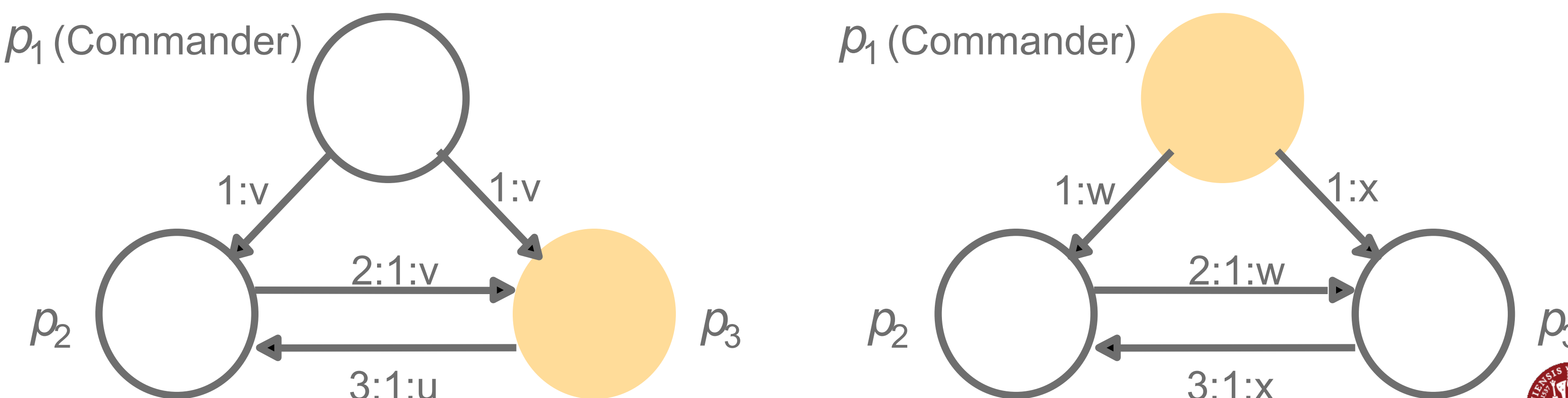
Byzantine Generals

- **Termination**: Eventually each correct process sets its decision variable.
- **Agreement**: The decision value of all The decision value of all correct processes is the same: if pi and pj are correct and have entered their decided state, then di=dj (for all i,j=1..N).
- **Integrity**: If the commander is correct, then then all correct processes decide on the value that the commander proposed.

Impossibility with Three Processes and Solution in a Synchronous System



Faulty processes are shown coloured



Faulty processes are shown coloured

Summary

- Many techniques for redundancy
- Replication widely used technique in practice
- Many flavors
  - State-machine replication
  - Asynchronous replication
    - Primary-Site
    - Peer-to-Peer
  - Synchronous replication
    - Read-Any, Write-All
    - Quorums
  - Tons of combinations of flavors possible!
    - E.g., primary-site + synchronous
  - Tons of variations in implementation according to failure model!
    - E.g., fail-stop, crash, Byzantine

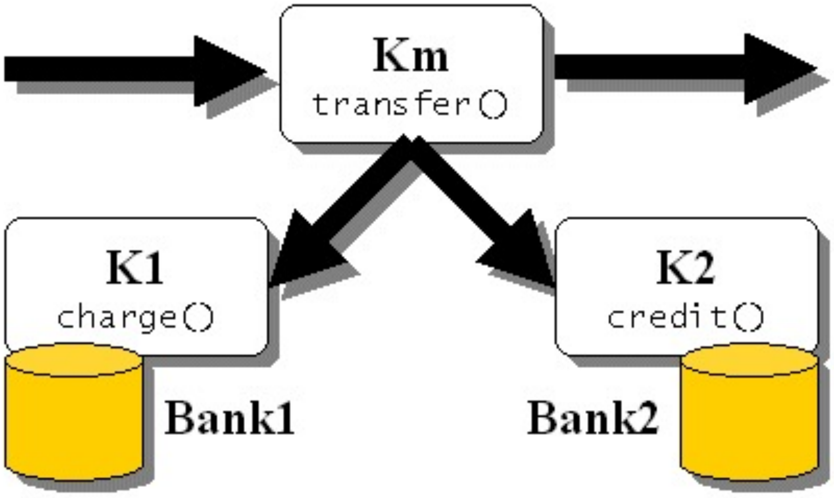
Questions so far?

Distributed Transactions

- Users should be able to write Xacts accessing multiple sites just like local Xacts

- Enforcing ACID calls for distributed locking, recovery, and commit protocols

- Hard to scale in number of sites in general
  - Use partitioning/replication techniques for trade-offs



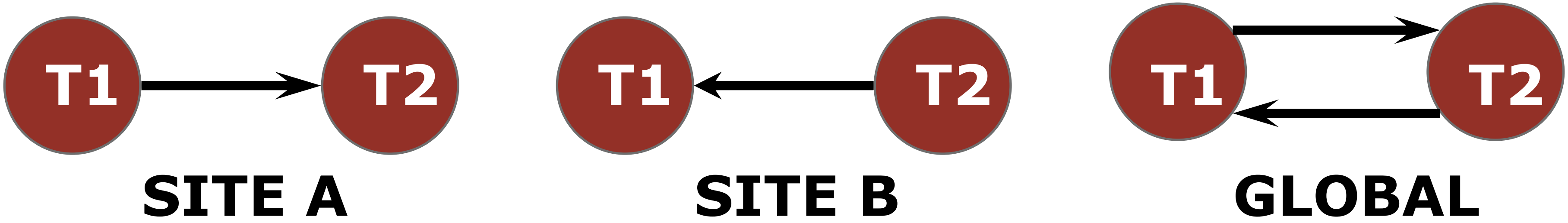
Source: Ramakrishnan & Gehrke (partial)

Distributed Locking

- How do we manage locks for objects across many sites?
- Centralized: One site does all locking
  - Vulnerable to single site failure
- Distributed: Locking for an object done at site where the object is stored

Distributed Deadlock Detection

- Each site maintains a local waits-for graph
- A global deadlock might exist even if the local graphs contain no cycles:



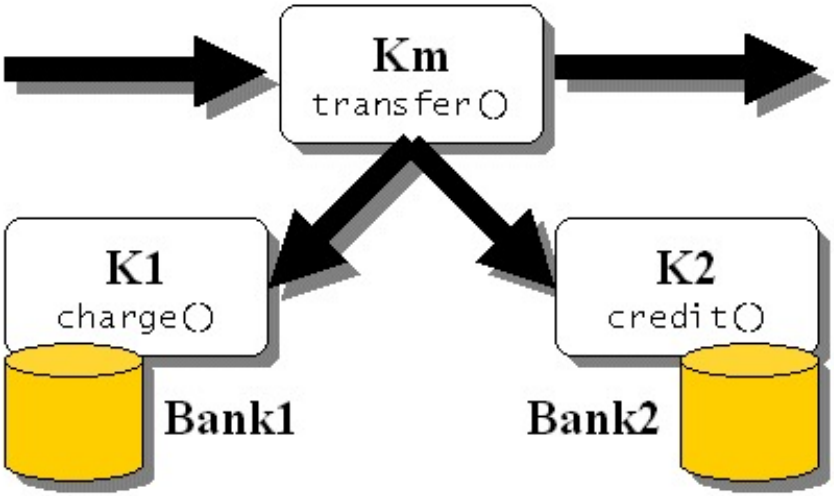
- Three solutions
  - Centralized: send all local graphs to one site
  - Hierarchical: organize sites into a hierarchy and send local graphs to parent in the hierarchy
  - Timeout: abort Xact if it waits too long

Source: Ramakrishnan & Gehrke (partial)

Distributed Recovery

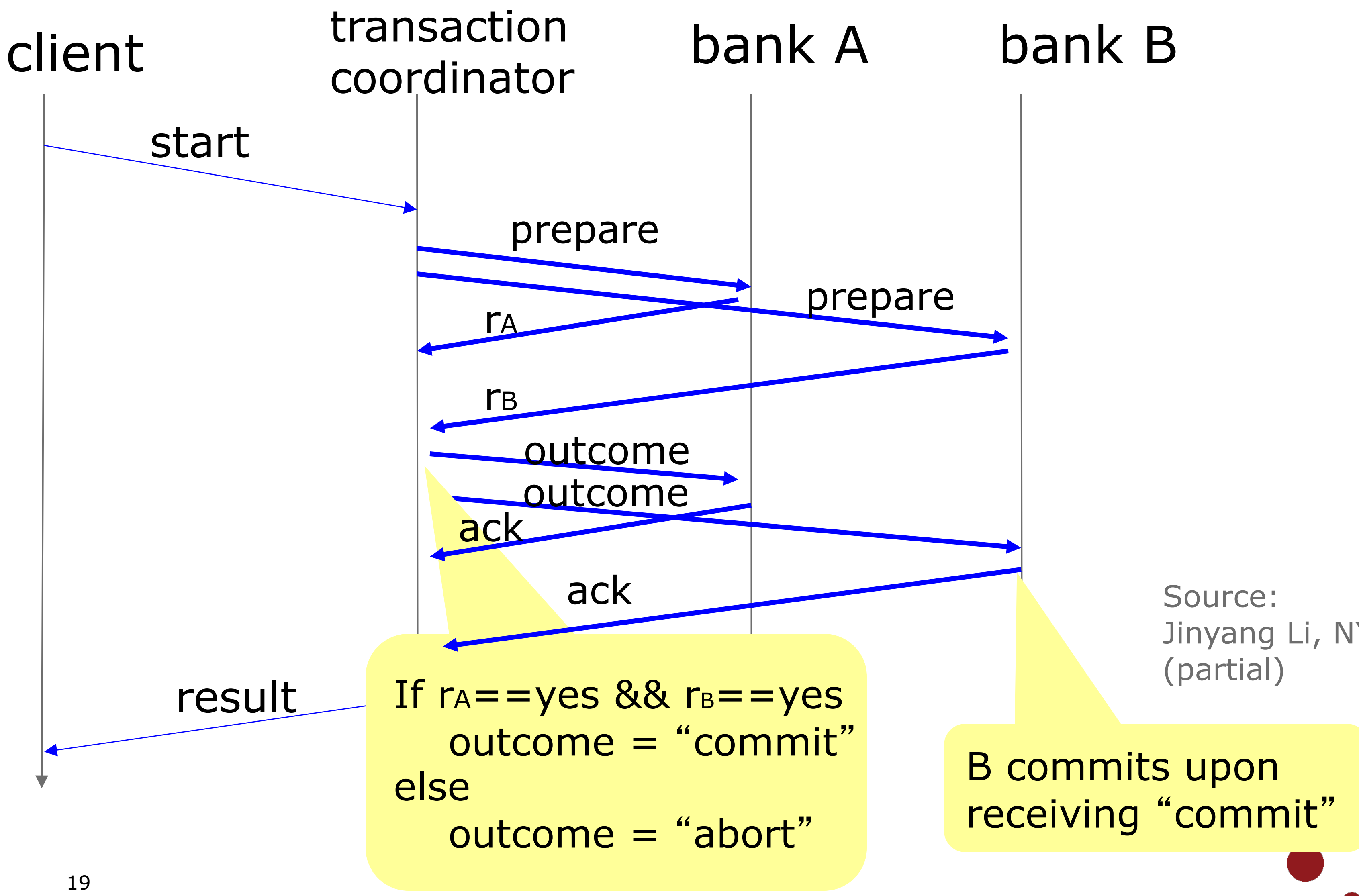
- New issues:
  - New kinds of failure, e.g., links and remote sites
  - If "sub-transactions" of a Xact execute at different sites, all or none must commit

    → Need a commit protocol to achieve this
- A log is maintained at each site, as in a centralized DBMS, and commit protocol actions are additionally logged



Source: Ramakrishnan & Gehrke (partial)

Two-Phase Commit (2PC)



Source:
Jinyang Li, NYU
(partial)

Comments on 2PC

- Two rounds of communication: first, voting; then, termination
  - Both initiated by coordinator
- **Any site** can decide to **abort** an Xact
- Every msg reflects a **decision** by the sender
  - To ensure that this decision survives failures, it is first **recorded in the local log**.
- All commit protocol log recs for an Xact contain Xactid and Coordinatorid
  - The coordinator's abort/commit record also includes ids of all subordinates/cohorts.

Source: Ramakrishnan & Gehrke (partial)

Discussion of Failures Scenarios

- Coordinator times out waiting for subordinate's "yes/no" response
  - Can coordinator unilaterally decide to commit? No
  - Can coordinator unilaterally decide to abort? Yes

- If subordinate *i* responded with "no" …
  - Can it unilaterally abort? Yes
- If subordinate *i* responded with "yes" …
  - Can it unilaterally abort? No
  - Can it unilaterally commit? No

WHY?

Source: Jinyang Li, NYU (partial)

Restart After a Failure at a Site

- If we have a commit or abort log rec for Xact T, but not an end rec, must redo/undo T
  - If this site is the coordinator for T, keep sending **commit/abort** msgs to subs until **acks** received
- If we have a prepare log rec for Xact T, but not commit/abort, this site is a subordinate for T
  - Repeatedly contact the coordinator to find status of T, then write **commit/abort** log rec; redo/undo T; and write **end** log rec
- If we don't have even a prepare log rec for T, unilaterally abort and undo T
  - This site may be coordinator! If so, subs may send msgs

Blocking

- If coordinator for Xact T fails, subordinates who have voted yes cannot decide whether to commit or abort T until coordinator recovers
- T is blocked

Link and Remote Site Failures

- If a remote site does not respond during the commit protocol for Xact T, either because the site failed or the link failed

- If the current site is the coordinator for T, should abort T
- If the current site is a subordinate, and has not yet voted yes, it should abort T
- If the current site is a subordinate and has voted yes, it is blocked until the coordinator responds

Source: Ramakrishnan & Gehrke (partial)

2PC with Presumed Abort

- When coordinator aborts T, it undoes T and removes it from the Xact Table immediately
  - Doesn't wait for **acks**; "presumes abort" if Xact not in Xact Table. Names of subs not recorded in **abort** log rec
- Subordinates do not send acks on abort
- If subxact does not do updates, it responds to prepare msg with reader instead of yes/no
- Coordinator subsequently ignores readers
- If all subxacts are readers, 2nd phase not needed

What should we learn today?

- Explain the difficulties of guaranteeing atomicity in a replicated distributed system
- Explain the notion of state-machine replication and the ISIS algorithm to totally ordered multicast among replicas
- Describe the implications of the FLP impossibility result and possible workarounds
- Explain mechanisms necessary for distributed transactions, such as distributed locking and distributed recovery
- Explain the operation of the two-phase commit protocol (2PC)
- Predict outcomes of 2PC under failure scenarios